Communication, Navigation and Control of an Autonomous Mobile Robot for Arctic and Antarctic Science

Diploma Thesis

by

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Abstract

This Thesis describes two different main fields of work on the Cool Robot. Cool Robot is a low budget, autonomous mobile robot. The mechanical design and layout was made as an earlier part of a Diploma Thesis. Most of the mechanical parts were already produced. This thesis describes the assembly process for the Cool Robot. What has to be done and which is the correct sequence are questions that are answered in the Thesis. However, the main parts of this Thesis deal with the overall navigation algorithm, the control and the communication and data storage. On the navigation side, the realization of an open loop course correction is evaluated and shown. The goal is an autonomous waypoint following path with a top speed of over 1 m/s. The navigation is therefor entirely based on GPS-data. The robot‘s main control is done with a 8 bit microcontoller which controls the brushless DC-motors in velocity mode.

The communication part deals with the connection between the robot and a laptop or desktop PC through a handheld radio with radio modem. The communication protocol will be the focus here. The preparation for an implementation of the IRIDIUM connection is also done in this Thesis.

All different kinds of sensor data, e.g., motor currents, etc. have to be logged and evaluated. Data logging on the main microcontroller itself or an external Datalogger will be aquired.

Statement

Hereby I do state that this work has been prepared by myself and with the help which is referred within this thesis.

Hanover, N.H.,03/29/2005

Goetz Dietrich

Toni Zettl

Foreword

This work is supported by the National Science Foundation grant OPP-0343328.

We would like to thank

Prof. Laura Ray for her great support and help, whenever we needed it. With her advice she pointed us always in the right direction and led us forward.

Dr. James H. Lever for sharing his exceeding knowledge and experience in the field of Antarctic Science associated with robotics.

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The Thayer Machine shop for their ear and hints in all mechanical questions.

The Thayer Instrument room for their supply with all devices and parts needed.

Thank you for making this exchange a great experience.

Hanover, 03/29/2005

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List of symbols and abbreviations

ADC	Analog to Digital Converter
Baud	One signalling element per second.
bp	basing point
char	8 bit character
cp[1]	current point for navigation use
cp[2]	last current point used for current bearing
CR	Carriage Return also `'\r'`
$\overline{CS}$	Chip Select - is used to start a conversion on the selected channel
CTS	Clear To Send. A flow control signal in serial interfaces.
DCD	Data Carrier Detect. This signal indicates a connection to the far-end modem for data transfer.
DAC	Digital to Analog Converter
DIN	Digital Input for a serial port
DOUT	Digital Output line for a serial port
DSR	Data Set Ready. Another flow control signal.
DTE	Data Terminal Equipment e.g. a personal computer running terminal software.
DTR	Data Terminal Ready. Yet another flow control signal.
float	32 bit IEEE-floating point
GPRMC	Recommended Minimum Specific GPS-data
GPSPosition	structure implemented in the code for latitude and longitude of a position
GSM	Global System for Mobile communications.
ICD-GPS-200	Interface Control Document defining characteristics of and data for the GPS L1 and L2 Signals in Space (SIS)

int	16 bit signed integer value
I/O	Input and Output
IRLP	Iridium Radio Link Protocol
ISU	Individual Subscriber Unit (IRIDIUM modem)
lat	latitude
LF	Line Feed, same as new line `'\n'`
lon	longitude
NMEA	National Marine Electronics Association
NMEA 0183	Interface Standard that defines specific sentence formats for a 4800-baud serial data bus
PTT	Push To Talk
RI	(V.24 Signal) Ring Indicate. ISU signal that indicates an incoming call.
RS232	Today named EIA232 and is a common interface standard for data communication
RTS	Request To Send.
RX	Receive signal
SCLK	Serial Clock - Internal Clock of Jackrabbit
SG	Signal Ground
SPI	Serial Peripheral Interface (three wire)
TTFF	Time To First Fix
TX	Transmit signal
wp	waypoint
XON/XOFF	A standard flow control method.

Chapter 1

Introduction

The Antarctic Plateau - a large, high altitude mass of ice and snow, covering most of Antarctica and impacts the atmospheric circulation of the Southern Hemisphere. Figure 1.1 shows a satellite photo of the entire continent. The Antarctic Plateau is composed of the region highlighted.

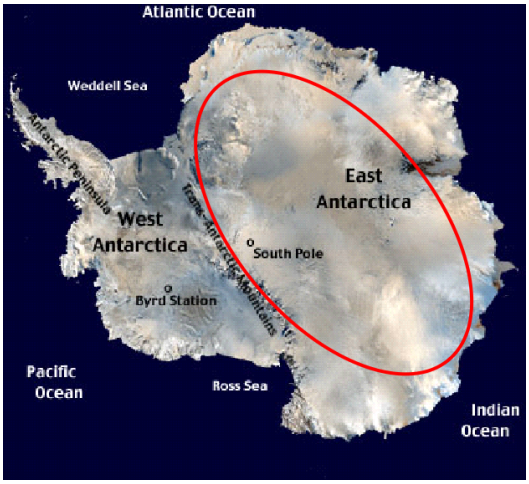


Figure 1.1: *Satellite Photo of Antarctica (Lever)*

It is of course extremely cold and dry, but it is also very high and the atmosphere above the plateau is very calm with low wind speeds at all latitudes. That makes the Antarctic Plateau a unique location to study the upper atmosphere at high magnetic latitudes, providing a stable environment for sensitive instruments that measure the interaction between the solar wind and

the Earth’s magnetosphere, ionosphere, and thermosphere [1].

Few Robots have been build to discover the Antarctic Plateau. They were very heavy and driven by combustion engines. These expeditions need either a high assignment of personnel, which is a problem in the harsh weather conditions in Antarctica, or a large transportation capacity which is very expensive, limited by the small size of the Twin Otter arid transport aircraft flying within Antarctica and entail hazards at remote landing and takeoff sites. Carnegie Mellon University for example developed NOMAD, a 725 kg gasoline-powered robot for polar and desert environments with a size of 2.4x2.4x2.4m [2]. The much smaller Spirit and Opportunity are Mars Exploration Rovers from NASA/JPL. Each 2.3x 1.6x 1.5m rover weighs 174 kg and has a top speed of 5 cm/s [3] and is powered by a multi-panel solar array.

The task was to build an Autonomous Mobile Robot which can be released at the South Pole station and traverse on the Antarctic Plateau during the austral summer within a range of 500 km in a time of 2 weeks without any maintenance. That is possible, because the robot is powered by renewable energy, the sun. The Antarctic Plateau gives very good reasons for using solar energy. During the austral summer month the direct insolation from the sun averages 1000 W/m^2. Also the reflected sunlight by the large flat snow areas is significant. The robot should have an empty mass of less than 75kg and should fit in the Twin Otter aircraft. Figure 1.2 shows the completed robot chassis.

Figure 1.2: *CoolRobot climbing sastrugi feature*

The basis for our work was the Diploma Thesis from Guido Gravenkötter and Gunnar Hamann [4] and the honor‘s thesis of Alex Price [5]. Reference [5] deals with the conceptional work on the robot and the major influence on the design of a solar powered robot. Hamann‘s and Gravenkoetter‘s contribution was to prove the viability of the project. They tested different components such as the brushless dc-motors, the li-ion batteries and the power supply in a cold chamber to see the influence of cold temperatures down to -40° C.The conclusion was that the new generation of solar panels will provide enough energy needed for the propulsion.The other conclusion of [4] was that the navigation has to be based on waypoints and GPS data only, because a magnetic compass does not work on the high magnetic latitudes on the Antarctic Plateau.

Reference [5] completed the robot design, including CAD models of all components and structural analysis. The mechanical design of the robot is based on a very light but strong honeycomb composite made of fiberglas and Nomex.

This thesis describes three different parts of work on the Cool Robot:

1. assembling of the chassis
2. navigation and control
3. communication and datalogging

Table 1.1: *Main topics of work on Cool Robot.*

The first part is the assembling of the honeycomb chassis and the motors and drive trains.

CoolRobot project started in winter 2003/2004 with the conceptional work. During the summer 2004 Alex Streeter, Alex Price and Dan Denton made most of the mechanical parts for the robot. The honeycomb panels were cut in pieces for the main chassis, the solar panel attachment arms the stiffeners, and the lid. The EAD-brushless motors were mounted to the gearhead and ready for their implementation in the chassis. The aluminum rims for the 16 inch or the 20 inch ATV tires were welded to the axis. On the logic side, the jackrabbit itself was ready for testing, because it was mounted to the evaluation board. The circuit for the 8 channel Analog Digital Converter MAX186 for reading the analog sensors and the Digital Analog Converter MAX536 to control the motors was build. The design of the solar power

system is the work of Alex Streeter's M.S. Thesis. Five separate, custom-built solar panels feed power onto a common bus, which is then distributed to the motors and housekeeping electronics. A bank of Li-Ion batteries act as a buffer for the bus and provide auxiliary power. The first part of our work was to assemble the chassis, adapt the motors to the chassis, and provide the support tubes for the axis. Configurating the microcontroller to communicate with the ADC the DAC, the GPS unit, the Datalogger and the modem would be the main part of our work. Finally, we had to program the different algorithms to drive the motors, read the different sensors, communicate with the modems, read the gps-data, and control the robot in various modes of operation.

Toni‘s main tasks are the communication between the robot and a human operator and the storage and retrieval of data the robot collects during it's journey. The only way to stay in touch with the robot while it is traveling around on the Antarctic Plateau is a connection over IRIDIUM-modem, which is at the moment the only provider of truly global mobile satellite voice and data solutions. The system provides a complete coverage of the earth‘s oceans, airways and most important for our application, the polar regions. With this connection the robot is able to report problems, transmit a portion of the collected data, or request new waypoints. On the other hand, an operator has the possibility to check the condition of the robot, request data and send new or changed waypoints. When the robot is deployed in the Antarctic it will equipped with an IRIDIUM transceiver. The big disadvantage of this system is the high price for this unlimited availability. The transceiver itself is priced around $1200 and every minute of connection costs $2 within the United States and $7 elsewhere in the world. Therefore another, cheaper system will be used during the development of the robot and the first field tests in Greenland. The easiest way to establish a wireless connection and transmit digital data is a radio connection using a data modem. With the help of two handheld radios and two radio modems one is able to control the motion of the CoolRobot manually or monitor the behaviour of the machine while navigating autonomously over a distance of approximately 2 km.

The CoolRobot will also be equipped with a datalogger to record scientific data from the payload. This data is analog and can be retrieved when the robot returns to its base. Especially during testing and the first run in the Antarctic all the sensor data the robot uses is a matter of particular interest. So, all this digital data will be stored too. The latest sensor-readings will be

stored within the limited flash memory of the microcontroller. If the robot encounters a critical situation this data will be send to the operator who then is able to reconstruct the situation of the robot. Older data will be filtered and passed to the datalogger. Thus, one can reconstruct the behaviour and condition of the robot during the whole journey.

Goetz deals with the overall control and navigation algorithm based on waypoint following through GPS. The robot‘s main intelligence are two microprocessors which are programmed in Dynamic C a computer language similar to C++. One is used for the power management, which is Alex Streeter’s M.S.thesis. The second microcontroller is for communication. It communicates with the GPS-Receiver to get the GPS-data, with a Digital-Analog-Converter to control the 4 brushless dc-motors and with an Analog-Digital-Converter which reads the sensors such as wheel speeds, motor currents and tilt angles. So the first task was to write the code for the microcontroller to take the readings from the Analog-Digital-Converter. Getting the GPS position data, it calculates basing points in a specified distance from each other on the track between waypoints and corrects its heading by open loop control.

The Antarctic Plateau consists of over 5 million square kilometers relatively flat terrain. The surface of the snow is very hard and has a lot of wind blown sastrugi with a size up to 25 cm which are a challenging task for the control and navigation algorithm. Figure 1.3 shows a typical sastrugi field along with a breifcase of height 20 cm. Navigation through sastrugi fields may cause brief dislocation of several degrees in bearing. But for the distance from waypoint to waypoint being about 50 kilometers, the distance off from its calculated track can be 20 meters or more without incurring major path deviations. Specific problems the sastrugis can cause are high centering and tipping over. To avoid high centering, the wheel speed sensors and the motor currents are set up to detect wheels that are not in contact with the snow. The bottom of the robot is plated with polyethylene, which has a very slick surface to make a slide to one side easier, enabling a control routine to get unstuck. (see chapter 4.5.3) Dr. James Lever took a picture on Ross Ice Shelf while travelling on the traverse from McMurdo station to the Leverett Glacier and Polar Plateau in december 2004. The picture shows the wind blown sastrugi features on Ross Ice Shelf with a notebook 20 cm large.

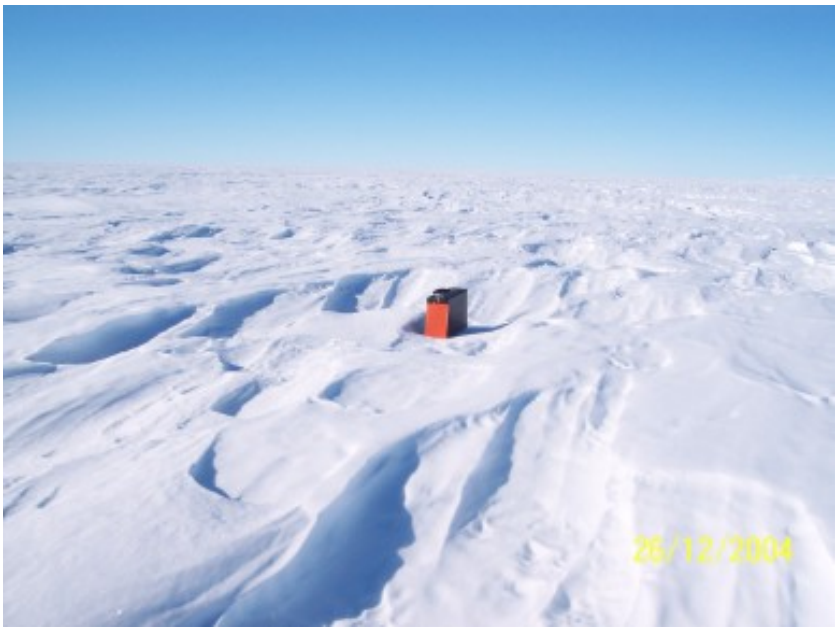


Figure 1.3: *Sastrugie features in Antarctica with 8 inch notebook for scaling*

To avoid the robot from tipping over, the 3-axis-tilt-sensor sends an interrupt to the control algorithm (see chapter 3.3.6).

This thesis starts with the assembling process for Cool Robot. We hope to give a summary of good practices for handling the honeycomb and some useful hints for refining next Cool Robot design.
Chapter 3 deals with the navigation of Cool Robot and provides all the necessary information to understand the basic mode of operation of the gps receiver as well as the main navigation program of Cool Robot and the monitoring of the analog sensors. In chapter 4 the control algorithms and the different drive modes are presented.
Chapter 5 introduces to the communication of CoolRobot. An overview of the future IRIDIUM communication is given, as well as a detailed description of the communication via radio link.
In chapter 6 a short outline on the data recording capabilities is presented. On the on hand using an external datalogger and on the other hand using the storage capabilities of the micro controller.
The structure and functionality of the CoolRobots software is described in detail in chapter 7. It can also be seen as a basic introduction to the DynamicC programming language with some

of its advantages and disadvantages for our application.

The test results such as current draw and energy consumption, waypoint following position data, and communcation protocol are presented in chapter 8

Chapter 2

Assembly process for Cool Robot

This chapter should give the reader an impression of how extensive even the assembly process for a simple robot is. By documenting weak points in the mechanical design and minor or major difficulties during the mechanical work, we want to achieve improvements in reliability and performance for the next generation of CoolRobots. The outcome should be an update that makes the next generation of CoolRobots better and a choice to beat! The combination of the honeycomb chassis and the new generation of solar cells with a high efficency helps CoolRobot to be an alternative solution for heavy and expensive robots such as NOMAD for example.

Figure 2.1: *Milled honeycomb getting bonded and put in place*

The structure of the honeycomb allows to mill just the fiberglass layer on one side, to fold or bend the panel perpendicular. When got into the project, almost all parts for the honey comb

chassis where already cut and milled by Alex Streeter and Alex Price. Some of the aluminum parts for the drive train where also available, like the wheels, axles and the retainers for the motors and gear heads. Thus, our task was finishing the remaining parts, and putting them together to a rolling chassis.

Figure 2.2: *Inserts with epoxy*

The first step was the gluing of the chassis body. Before actually gluing it together we had to drill holes for the support tubes and the inserts for mounting the motors and the top lid, since it is easier much easier to do this as while the body still is a flat piece of honey comb, instead of an upright box. Figure 2.2 shows the process of applying epoxy to an insert prior to securing the fastener to the chassis. Furthermore pieces of angle aluminum must be cut into length and sandblasted. The angle aluminum is used to reinforce the corners of the folded body, sandblasting them is necessary to roughen the surface and guarantee a good bond between aluminum and honeycomb. By the way, the contact surface of all aluminum parts were sandblasted and cleaned before their use. As adhesive a two part epoxy containing aluminum dust is used. It provides high strength and the ability to fill the spaces within the honey comb. The best choice to keep the folded body in place for as long as the two part epoxy needs to cure up was a welding table, since it provided the best possibilities to position the chassis using brackets on each side of the chassis. One rectangular corner was aligned with brackets, to start the gluing in this corner. All contact areas at the edges as well as the milled inside of the edges to bend up where covered with a thin layer of the epoxy. All four sides were folded up to right angle and the the remaining two sides were fixed by two more brackets. The result is shown in right half of figure 2.1. After aligning the chassis correctly the angle aluminum was glued to the insides of all four corners.

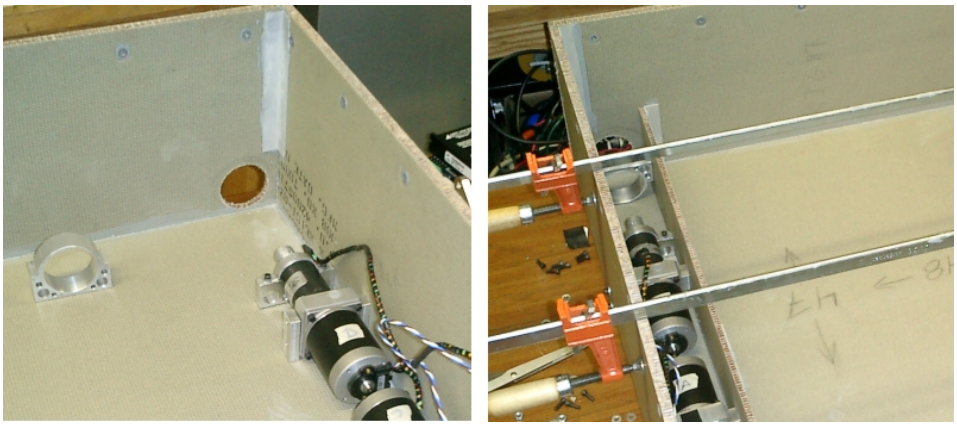


Figure 2.3: *Chassis without and with partition wall*

The next step was adding two partition walls to the corners of the chassis where the motors are located. Since the motors are screwed to the chassis box itself and the partition walls we also drilled the holes for this connection before gluing the walls to the box. That was not an ideal solution, since there is no guarantee for a correct alignment of the motors. Thus, on further generations of CoolRobots the holes in the partition walls and the chassis box should be drilled after adding the mounts for the axle to align the motors as exact as possible and avoid unnecessary high friction within the drive train. To add more strength to the partition walls angle anluminum was used to reinforce the connection on either side of the walls and on the bottom.

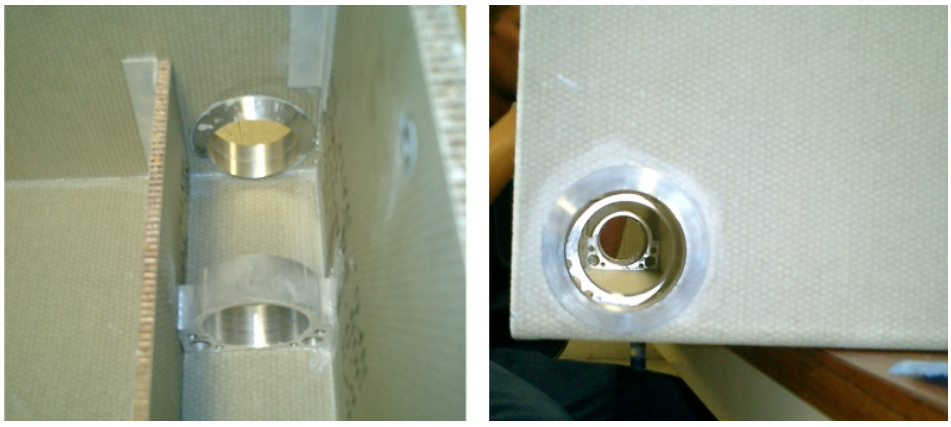


Figure 2.4: *Top view of the support tube mounts and view along one of the axles*

After that the mounts for the support tubes (see figure 2.4) were glued to the chassis. To assure an exact alignment of both support tubes on one axle a long piece of the aluminum tube used for the support tubes was used through the tube holes on both sides of the robot. The tube remained within the axle over night until the epoxy cured up completely. Since the mounts on the outside consist of two independent rings some of the epoxy could have reached the tube, thus to avoid gluing the tube to the mounts we moved it from time to time.

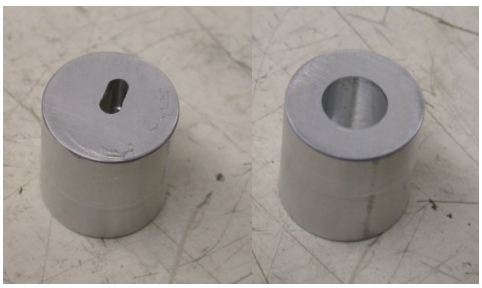


Figure 2.5: *The aluminum shaft collars*

In the meantime the shaft collars were milled and the inner parts of the rims were welded to the actual axles. Furthermore, all inserts were glued to the chassis, and the motor and gear heads were mounted too. For gluing the inserts we coated the contact areas with epoxy, put both parts with a screw and nut to the desired hole and tightened the screw carefully until both parts of the inserts engaged.

The next step was finishing the support tubes and gluing them in place. The tubes were cut to length and on one side the inner diameter of the tube was enlarged a little bit to the bearings within. Furthermore a groove for the retaining ring was milled to the very end of the tube. The finished support tube was now glued to the mounts also using the two part epoxy. After this step the whole drive train was mounted to the chassis, beginning with screwing the shaft collars to the gear head, then fitting the bearings to the support tubes and fastening them with the retaining rings. Now, the axles could be inserted and screwed to the shaft collars and finally the wheels were screwed to the axles. As the rolling chassis was finished the electronic components were added to the chassis. The motor controllers were mounted to the side walls of the chassis near their appropriate motor using two screws for each controller glued to the walls. By the time we finished the assembly to a drive able robot, the first test pieces of software were finished too. One of them was a routine to adjust the output of the motor controllers via the DynamicC compiler window and keyboard inputs. So we started first driving tests. At the very beginning we droe just within the building but we soon decided to take it outside to check its maneuverablity, speed and also the strength and flex of the chassis.

Figure 2.6 shows photos from the first outdoor tests.

Figure 2.6: *First moving test of Cool Robot*

After some testing with the robot, the decision was made that the robot should be equipped with 20 inch tires instead of the 16 inch tires it was running at the moment. The benefits herein are a 2 inch increased ground clearance and due to the fact the 20 inch tires are slightly wider also a decreased ground pressure and sinkage. Furthermore the tread pattern of the 20 inch tires seemed more efficient for driving on snow than the pattern of the 16 inch tires. So we switched to the larger tires. This procedure took almost one day, since it was quite a bit of work to remove the small tires from the rims. Removing the first half of the rims was pretty easy using clamps to compress the tire until one of the two halves was free. To remove the second half from the tire, we had to use clamps and wood to move it step by step. In contrast, putting the new tires on was pretty easy and involved putting both halves of the rims together with some new sealing compound and the new tires in between and inflating the tire to about 30psi until the tire pops into the correct place on the rim. To help the tires sliding on the rim some soap and water was used as lubricant.

The last part of the Assembly process was fitting the top lid to the robots chassis. The first step was cutting the sidewalls of the lid to their final height and drilling the holes for the inserts. This was not easy, since the inserts on the chassis sidewalls were not exactly in a straight line and in perfectly equal distances to each other. So we had to custom fit almost every hole to achieve as much matching inserts on the top lid and the chassis itself. The exact fitting was done while gluing the top lid together: we glued one side of the lid at a time and focused the

inserts of the top lid by screwing them to their respective insert on the chassis. Doing one side after the other in this manner we assured the best possible fitting. The next day when the epoxy on all inserts was cured completely we started with the actual cluing of the top lid. We screwed one side of the lid to the chassis and then coated all necessary contact areas with epoxy. After this the lid was folded down to the chassis and the other three sides were focused too. Since almost all insert holes were focused with screws the lid cured up keeping exactly the right shape. Finally a hole was drilled to the middle of the top lid trough which cables for the GPS antenna, the radio and the Jackrabbits programming cable can be lead.

During all the testing the Cool Robot's concept proved itself by being an easy and reliable robot. The only real problem we encountered during this time was the connection between gear head and axle. The aluminum shaft collars produced some problems with the drive train. The aluminum does not provide enough strength in this application, there is too much slackness at the key on the gear heads axle. Thus the wheels can turn several degrees without any movement of the motors. Furthermore the aluminum of the shaft collars and the robots axle bond together due to some small parts of aluminum in between. This made big problems when trying to disassemble the drive train. Therefore the suggestion is to use another material, e.g. steel, for the shaft collars in the future. Maybe not only on further generations of Cool Robot but also before testing in Greenland and definitely before deploying it in the Antarctic.

Chapter 3

The navigation and monitoring elements

The navigation of Cool Robot is limited by the budget restrictions for the project. Cool Robot is a low cost autonomous robot for Antarctica. The fact that the magnetic South Pole and the geographic South Pole vary from each other does not have great effect on navigation by magnetic compass in our latitudes, but the bearing difference does increase the closer one gets to the Poles. Precise bearing information for navigation use on the Antarctic Plateau can be provided by a triaxial magnetic compass but is not intended for our project.

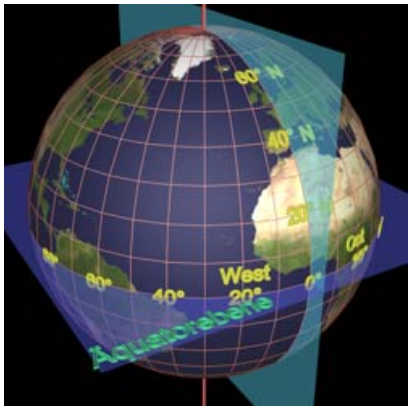


Figure 3.1: *Lat and lon on earth*

Due to expense, the navigation for Cool Robot is based entirely on GPS(Global Positioning System) (see chapter 3.1).

Coordinate planes for determining positions on earth have existed for many centuries. History has brought up many different ways of longimetry and goniometry. Today the system of latitude, longitude and height is the most popular one. The prime meridian in Greenwich and the equator are the references for the definition of latitude and longitude. The latitude degrees start from the equator with 0° to North and South Pole with 90°‘N‘ or ‘S‘. The distance between two latitude degrees is

always the same and does not change. For one latitude degree being divided into 60 arc minutes which have a distance of 1 nautic mile, the distance between two degrees is 111.136 km. One latitude minute is again divided into 60 seconds. Longitude degrees and minutes are also divided into 60 arc minutes and these again in 60 arc seconds. The longitude is measured up to 180° west or east. The distance between two longitude degrees is not constant and changes with latitude.

The following chapter deals with the main navigation algorithm of the Cool Robot. The most important terms are explained here for better understanding:

waypoint: A waypoint is a GPS position consisting of latitude and longitude transmitted to the robot by the user. A maximum of 100 waypoints can be saved in an array. By means of the waypoint coordinates and the current position, the distance to the waypoint and the heading can be calculated.

current point: A GPS data string in NMEA format from which the current position of the robot is parsed. Used to calculate and correct the traveled course.

basing point: A GPS position generated in a distance given by the user on the track connecting two waypoints. In our case they are generated every 1000 m to reduce the offset from the track.

initial distance: The distance between two waypoints. For the first navigation cycle at startup, the initial distance is the distance from the first current position to the first active waypoint. The initial distance does not change during navigation until the waypoint is reached and the next waypoint is activated.

initail bearing: The bearing between two waypoints. For the first navigation cycle at startup, the initial bearing is the bearing from the first current position to the first active waypoint. The initial bearing does also not change and is calculated together with the initial distance.

distance to waypoint/ basing point/ current distance: The distance between the current position and the mentioned point in km. The current distance is the distance between the last two current positions.

bearing to waypoint/ basing point/ current bearing/ off bearing: The bearing on which one would reach the waypoint/ basing point when traveling on. The bearing is measured in true degrees from north, counted clockwise. The current bearing is calculated between the last two current positions. The off bearing is the number of degrees the robot needs to turn to head to the desired position (e.g. waypoint).

offset from track: The offset from track is the smallest distance to a direct connection between two waypoints. The length of the perpendicular to the track through the current position.

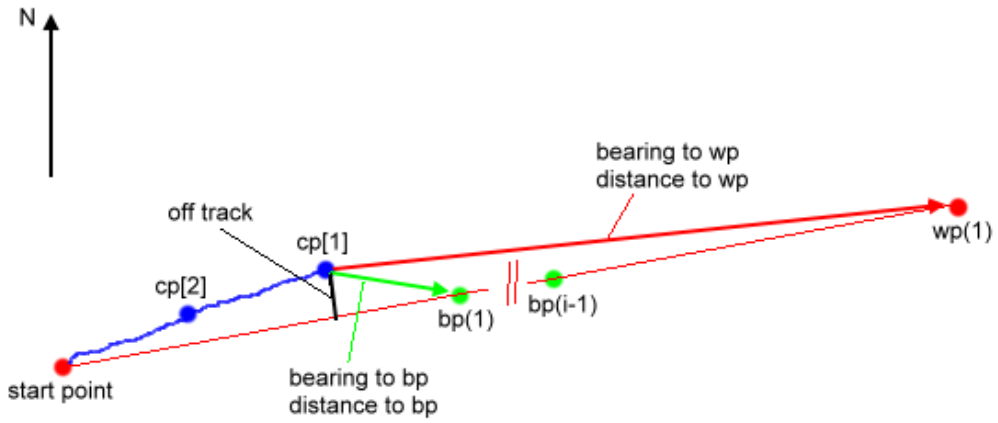


Figure 3.2: *Visualization of most important terms for GPS navigation*

The main principle of the navigation is waypoint following (see chapter3.2). Cool Robot receives GPS data, which includes latitude and longitude for the current position. The user provides a list of waypoints he wants the robot to reach. By calculating its current position the robot then travels on a predetermined path to the next waypoint. When within a certain range of that waypoint, the path to the next waypoint will be calculated. For two waypoints being away from each other over 10 km, the robot generates basing points (see chapter 3.2) on the track in a distance of 1 km to each other.

3.1 GPS Navigation

Everybody has heard about Global Positioning System, but how exactly can a robot travel in Antarctica only relying on the GPS Signal?

The NAVigation Satellite Timing and Ranging (NAVSTAR) Global Positioning System is an all weather, radio based, satellite navigation system that enables users to accurately determine 3- dimensional position, velocity and time worldwide. The GPS-System was originally invented for the military and is run by the American Department of Defense. The System consists of 24 satellites operating in 12-hour orbits in an altitude of 20,200 km around the Earth that emit signals which can be received on Earth by GPS receivers. The constellation is divided in six orbital planes, each with 4 satellites equally spaced around the equator and inclined at 55 degrees. The GPS receiver on earth determines position by passive multi-lateration. With knowledge of the transmission time for each signal, the distance to each satellite with known coordinates in space can be calculated.

To determine the correct 3 dimensional position (latitude, longitude and altitude) the receiver needs the clock offset. Therefore, a minimum of four satellite observations are required to mathematically solve for the four unknown receiver parameters. If the altitude is known, then only three satellite observations are required. However, that is not a guarantee for consistent accuracy. The accuracy depends on the number of satellites tracked. With 5 or more satellites the receiver‘s position can be accurate up to a few meter (Figure 3.3). The accuracy can be increased up to less than 1 meter with Differential GPS (DGPS). Hereby the receiver‘s signal is corrected with a second GPS signal send out by a stationary GPS receiver on Earth. The correction signal is sent in a longwave signal. The correction stations are generally provided in coastal regions and driven by the coast guard. CoolRobot will have a DGPS receiver for the testing in Greenland but for the navigation during this thesis it is equipped with a Motorola Oncore M12+ receiver (see chapter 3.1.1).

Figure 3.3 shows some driven tracks against the background of the j parking lot on Dartmouth campus. The speed was around 1 mph. The gps position data was evaluated and charted with excel. It should be used to receive an impression on the GPS‘s accuracy. During the testing,

five satellites were tracked.

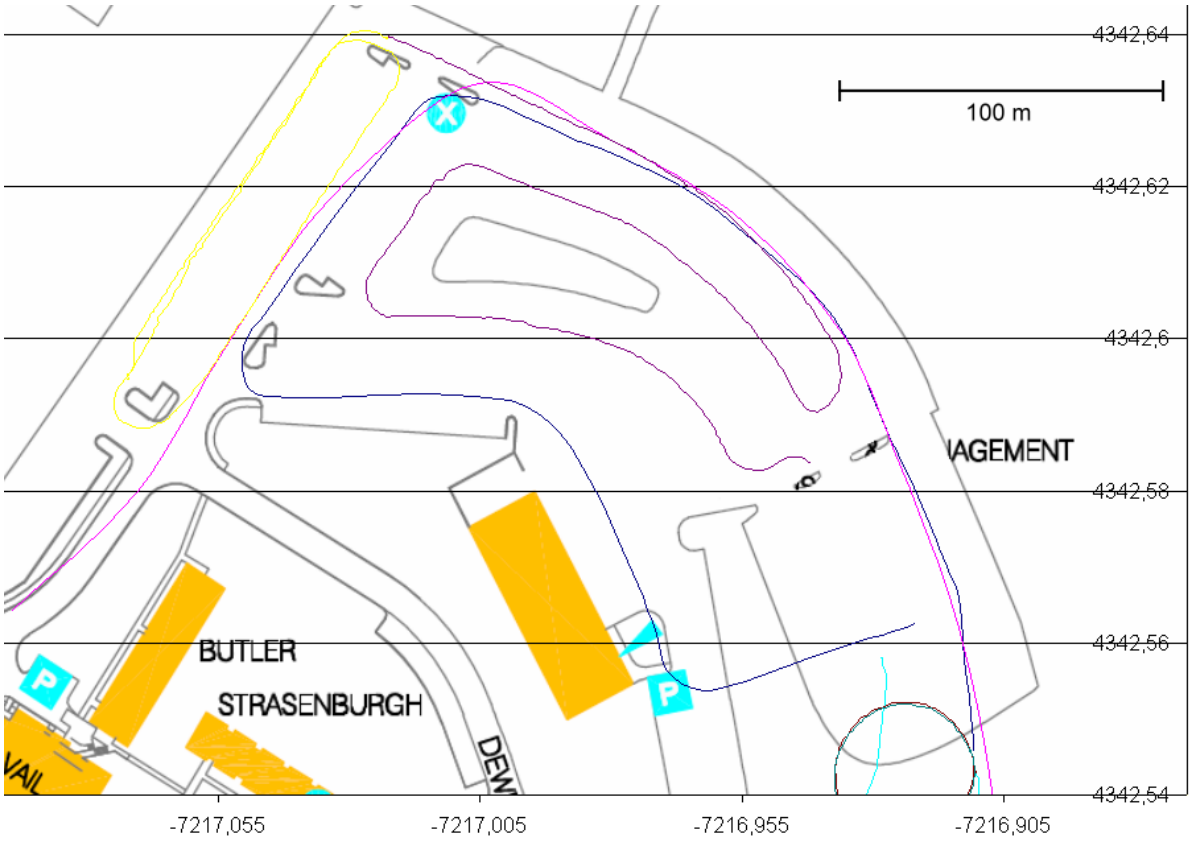


Figure 3.3: *GPS positioning test on j parking lot at Dartmouth*

Besides the latitude and longitude position information the NMEA-0183 GPS data string also includes information about speed over ground and current bearing. The speed over ground is accurate enough to tell a movement of the robot, even at low speeds around 0.5 m/s, whereas the bearing is of no use for the navigation algorithm. The GPS bearing is internally calculated with the two last positions. As the distance between two points apart 1 second in time, the distance between these points is 1 m, assumed 90 % of the robot‘s top speed. That makes a precise bearing calculation impossible. The result is, that the robot will have no usable information about the current heading, while making a turn or standing still on one point. The conclusion is to have an open loop course correction based on course GPS readings, or upgrade the robot if necessary with a triaxial magnetic compass.

3.1.1 The Motorola Oncore M12+ GPS receiver

The GPS receiver on the evaluation board M12+ is provided with +10 V supply voltage. The I/O-command format is Motorola Binary at 9600 baud. The commands can be used to initialize, configure and control the receiver. The receiver does also provide I/O-commands in NMEA-0183 format at 4800 baud, but these commands can only be used to change the transmitted GPS data string (e.g. output rate). For all I/O-commands see M12+ receiver user‘s guide chapter 5. The best way to initialize the receiver is by using the software WinOncore on a PC. The serial port has to be connected to the GPS receiver with the provided 9-pin serial cable. The serial port on the PC has to be opened at 9600 baud.

If the receiver is started up after a longer non-operated period of time, the user should allow the receiver 3 to 5 minutes to power up. That time is called TTFF (Time To First Fix). The receiver must now perform a Cold Start, where position, time, and almanac information are not available. The satellite almanac files each contain information about GPS reference week, the almanac reference time, required data to identify a satellite, satellite health status, longitude of orbital plane and more (see ICD-GPS-200 for detailed description). Note that a cold start is not a serious problem, but TTFF will be somewhat longer than if the information had been available. The main thing to keep in mind is that the receiver coming up in a Cold Start scenario is defaulted to Motorola Binary protocol, and NO MESSAGES are ACTIVE. The receiver is running through its normal housekeeping routines, developing new fix data, etc., but it will not send any of this data out of the serial port until it is requested.

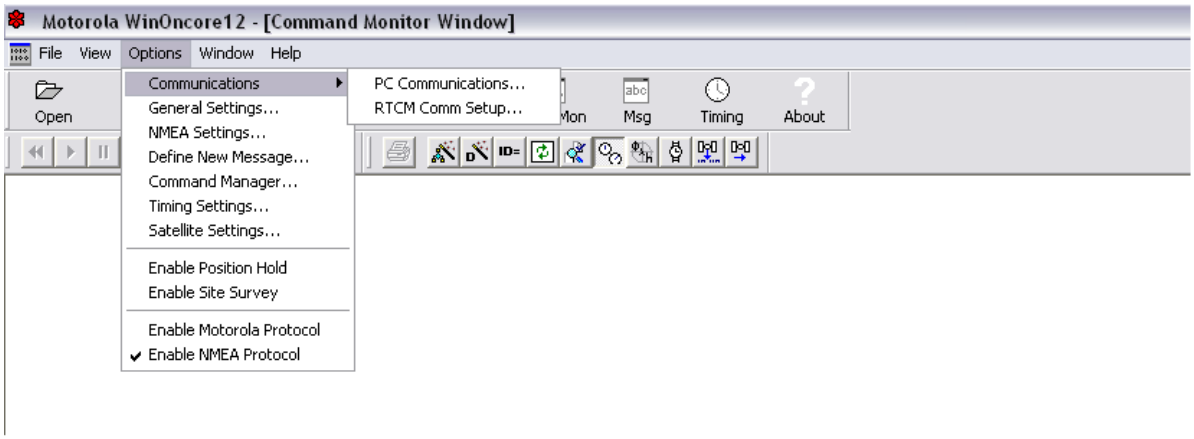


Figure 3.4: *Options to initialize the GPS unit to output NMEA data*

Using the software Winoncore, the receiver can be initialized easily by selecting the desired output format and rate from once a second to once every 9999 seconds. After setting the output format, NMEA Protocol has to be enabled (Figure 3.4).

The GPS data string sent to the serial port is displayed in the command monitor window (Figure 3.5) and accessed by "Cmd Mon". The receiver now is ready to be connected with serial port C on the Jackrabbit microcontroller (Figure 3.7).

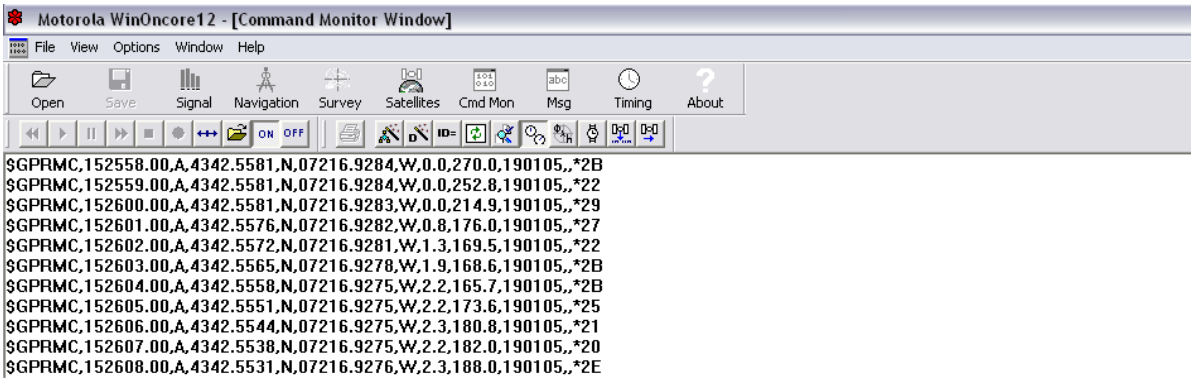


Figure 3.5: *WinOncore for Motorola M12+ GPS receiver with GPS data in NMEA format*

The software compiles the Motorola Binary I/O-commands to initialize or configure the GPS receiver. Once in NMEA format the user can decide between following different NMEA output messages:

Message	Description
GPGGA	GPS Fix Data
GPGLL	Geographic Position Latitude/Longitude
GPGSA	GPS DOP and Active Satellites
GPGSV	GPS Satellites in View
GPRMC	Recommended Minimum Specific GPS/Transit Data
GPVTG	Track Made Good and Ground Speed
GPZDA	Time and Date

Table 3.1: *NMEA-0183 Specification Revision 2.0.1.*

The easiest way to change the receiver‘s output is with the software. Otherwise see Motorola

M12+ GPS receiver user's guide chapter 5. For our application we decided for an output of the GPRMC message once per second:

```
$GPRMC,154425.00,A,4342.5660,N,07216.9153,W,2.4,338.0,190105,,*28
```

Figure 3.6: *GPRMC example message*

$GPRMC	message header
154425.00	UTC time of the position fix in hours, minutes, and seconds
A	current position fix status with A designating a valid position, and V an invalid
4342.5660	current latitude in degrees and minutes
N	direction of the latitude with N indicating North and S indicating South
07216.9153	current longitude in degrees and minutes
W	direction of the longitude with W indicating West and E indicating East
2.4	current ground-speed in knots
338.0	current direction, referenced to true North
190105	UTC date of the position fix
*28	checksum

Table 3.2: *GPRMC message.*

The M12+ receiver is used with the backup battery which is not necessary, but useful for saving setup information, especially the data output format and increasing the speed of satellite acquisition and fix determination when the receiver is powered up after a period of inactivity. Battery equipped M12+ receivers are fitted with rechargeable 5 mAh cells, sufficient for 2 weeks to a month of backup time, depending on temperature. To recharge the cell, the receiver must be powered up, a complete empty battery needs up to 24 hours of charge time. If set to default, the receiver can be configured with the software again.

The GPS receiver is connected to the alternate RS232 pins for serial port C on the Jackrabbit (J5). (rxc = pin4, txc = pin6, gnd = pin9) The connector for the receiver is a standard 9-pin serial connector and wired as shown.

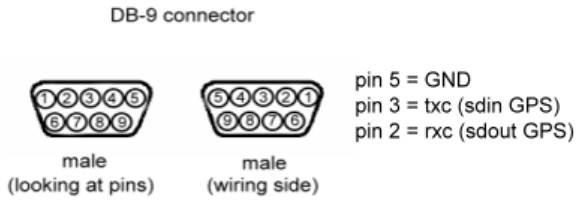


Figure 3.7: *Connector M12+*

3.2 Main program for autonomous navigation

The navigation function navigate is written in the library navigate.lib and follows the flowchart in Figure 3.8.

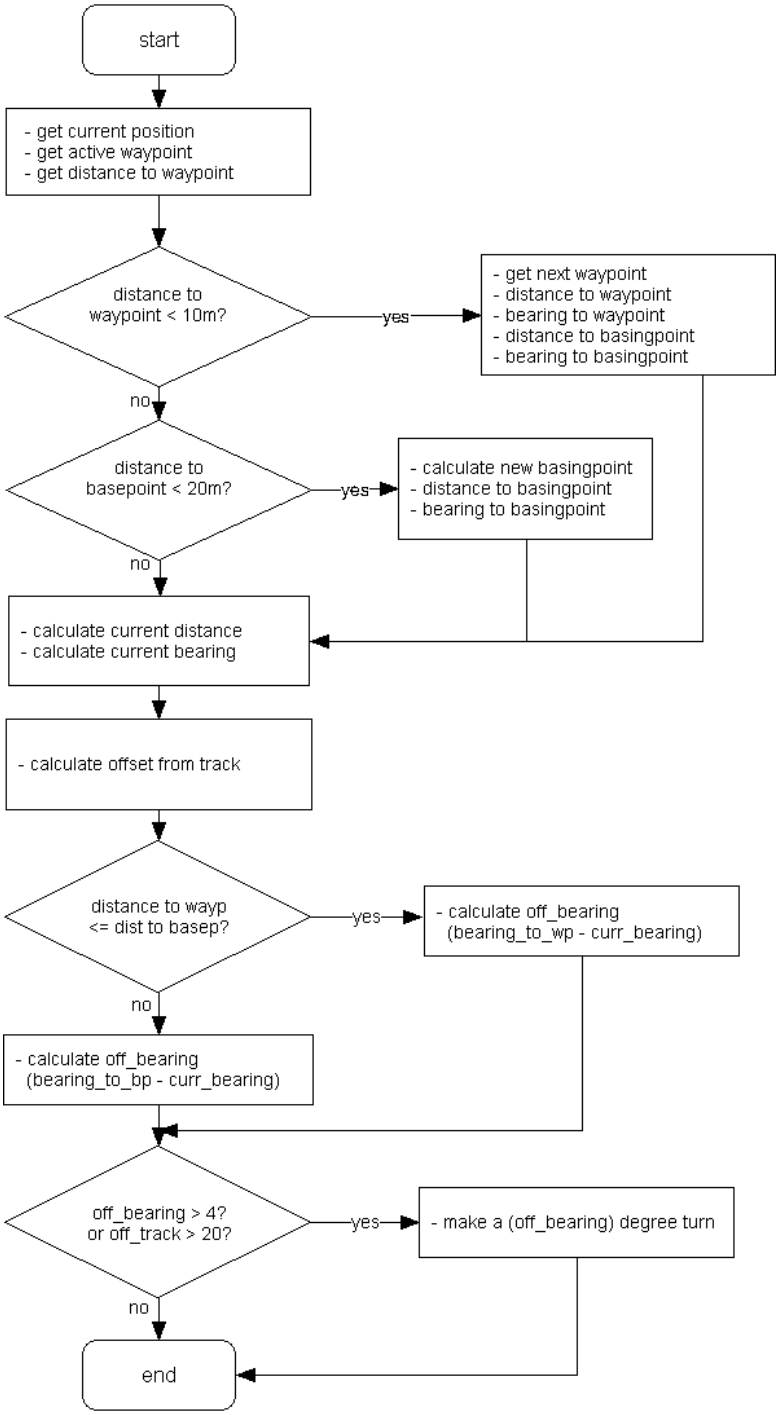


Figure 3.8: *Flowchart for basic navigation algorithm*

The navigate function is the heart of the navigation algorithm. It is a function called from the drive mode "wp_follow_full()" or the drive mode "wp_follow_partial()" in certain time distances. It makes the decision for a course correction (see chapter 4.4 for description of drive modes).

The NMEA-GPS data string is assigned to the function and the data string has to be parsed. Therefor the function "gps_get_position" in the gps.lib is called. The function compares the string header with the known NMEA messages, in our case "$GPRMC". If the header does not match any of the known messages, the function returns -1 as value. If the GPS data string is not valid, because the receiver is not tracking enough satellites, the function returns -2. If the header is known and the data string is valid, the function now parses the position data and stores it in a variable with the structure "GPSPosition" defined in the gps.lib. The structure "GPSPosition" consists of:

(int)	current_pos.lat_degrees
(float)	current_pos.lat_minutes
(char)	current_pos.lat_direction
(int)	current_pos.lon_degrees
(float)	current_pos.lon_minutes
(char)	current_pos.lon_direction

Table 3.3: *Sample structure GPSPosition current_pos.*

That makes an easy access to the integer part of the latitude and longitude possible: "current_ position->lat_degrees" .

The most important thing for the navigation algorithm is a correct transmission of the GPS-data string. There can be all different kinds of problems in parsing the correct GPS-position. To exclude the most transmission errors, the function to parse the NMEA-data string "gps_get _position" makes some comparisons. Programmed from Z-World was the checking of the header which are the first 6 characters. They also checked if the incoming string contains any valid GPS position data or if the number of satellites did not suffice for a position determination. I also implemented a comparison of the directions of latitude and longitude. If the header is not one of the known NMEA formats or if the NMEA-data is invalid, the navigation

algorithm will try to get a valid reading of GPS-data once every second until it succeeds. In the case of not having any valid readings for 30 seconds, adjusted by "GPS_inv_limit" the robot will change into manual drive mode without driving any distance. In that case a notice of "GPS parsing error" or "GPS sentence invalid" will be sent out to the modem. This notice will also be sent if one of these errors occured once but the robot will start navigating once received valid GPS-data.

If the current position was parsed properly, the active waypoint is selected from the array of waypoints given by the user. At startup the function recognizes that it was called for the first time if the variable "wp_start" is 0. Then the initial distance to the active waypoint in km is calculated with the function "gps_ground_distance" in the gps.lib. With the distance from startpoint to first active waypoint, the bearing to that waypoint in true degrees is calculated. A bearing value of 360° or 0° means the robot is heading to the geographic North Pole and 180° means the robot is pointing to the South Pole. Once in Antarctica, CoolRobot will have waypoints with a distance of 50 km or more. To assure that the offset from the track to each waypoint does not increase beyond a limit, basing points are generated in a predetermined distance to each other on the track from waypoint to waypoint. The distance to basing point "dist" is calculated in the "navigate" function at startup. The distance to the active waypoint is divided by 1000 m and the result is rounded off to an integer. The initial distance is then divided by that integer and will give a distance between basing points close to 1000 m. That calculation is made to make sure that there is a whole number of basing points between two waypoints and that the last basing point is the waypoint.

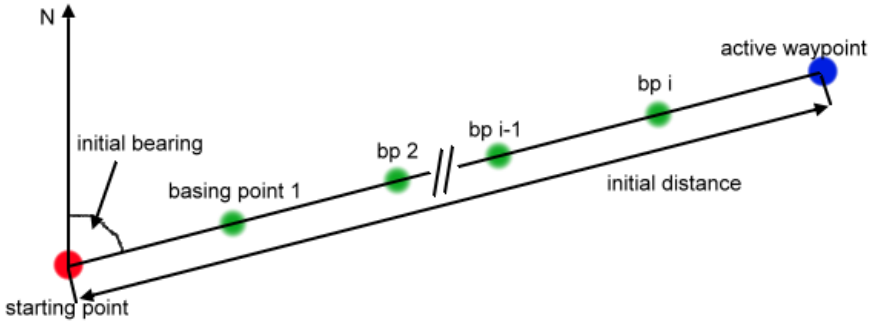


Figure 3.9: *Basingpoint and waypoint example (drawing)*

The last thing done in the startup procedure is that 1 is added to wp_start, so that the function does remember it’s starting point. If the navigation algorithm was called for the first time ("wp_start == 0"), the current position saved in "current_pos[1]" is also saved in "current_pos[2]. These two positions are used to calculate the robot‘s bearing. They are the traveled positions 30 seconds apart in time wheras the time is an adjustable parameter (tm_nav). For running through the navigation algorithm for the first time, there is no current position from the last navigation cycle. I had two different ideas of how to proceed on the startup in drive mode "w_follow_full". The first one is to place the robot pointing north. The current distance at startup is 0 km and the calculated bearing between the two sample points is also 0. So at startup Cool Robot thinks his heading is north and makes a turn for the off bearing degrees between -90° and 90° depending on the initial bearing. If the robot‘s heading is north, in the best case the turning to the desired heading takes one navigation cycle as outlined in Figure 3.10.

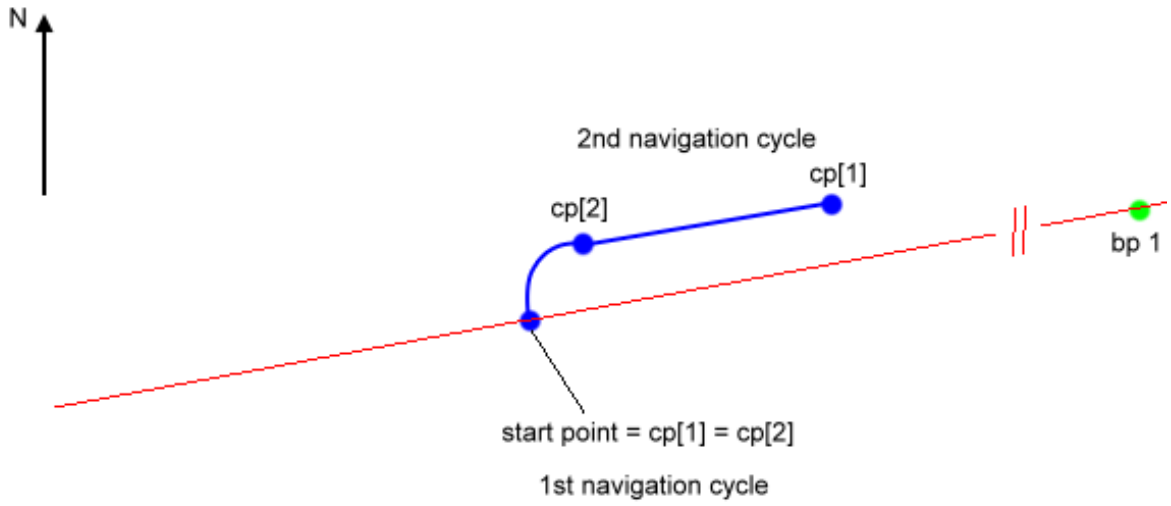


Figure 3.10: *Startup procedure 1 with Cool Robot pointing north*

In the worst case, the robot is pointing south instead of north at startup. That will not cause serious problems, but takes some more navigation cycles to head to the desired course to the waypoint or basing point as shown in Figure 3.11.

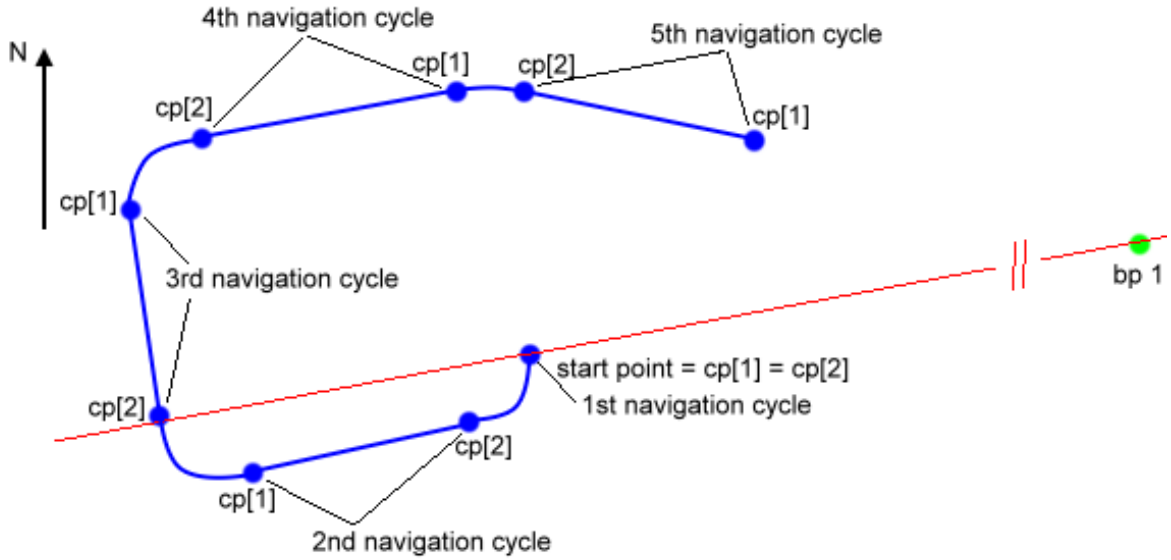


Figure 3.11: *Startup procedure 1 with Cool Robot pointing south*

The dimensions for the whole course correction procedure look larger than they are. Compared to the distance to the waypoint, the distance for the offset from the track caused by a south pointing at startup is only about 0.5%.

The second method to proceed during startup is to take the GPS-position first and parse it for current point[2]. Then the robot will speed up and drive straight ahead for x seconds, defined with "tm_nav" and then it will take the current position[1] and start the first navigation cycle as outlined in Figure 3.12. The advantage of the second method is, that the robot does not make any useless turns that are wrong, because it does not know its heading. The idea behind that is, that there will be a lot of interruptions forcing the robot to switch the drive mode from "wp_follow_full" to "high_wind_speed" or "high_centered". As the robot changes its heading in one of the different drive modes, it has no precise information on the current bearing without any movement once back in drive mode waypoint following at full speed or partial speed. To keep the number of navigation cycles to turn into the desired bearing as small as possible, method two is implemented in the naviation algorithm at this point. If the robot switches the drive mode to waypoint following it may drive 30 seconds in the wrong direction but recovers that at the first navigation cycle instead of possibly turning to the wrong direction.

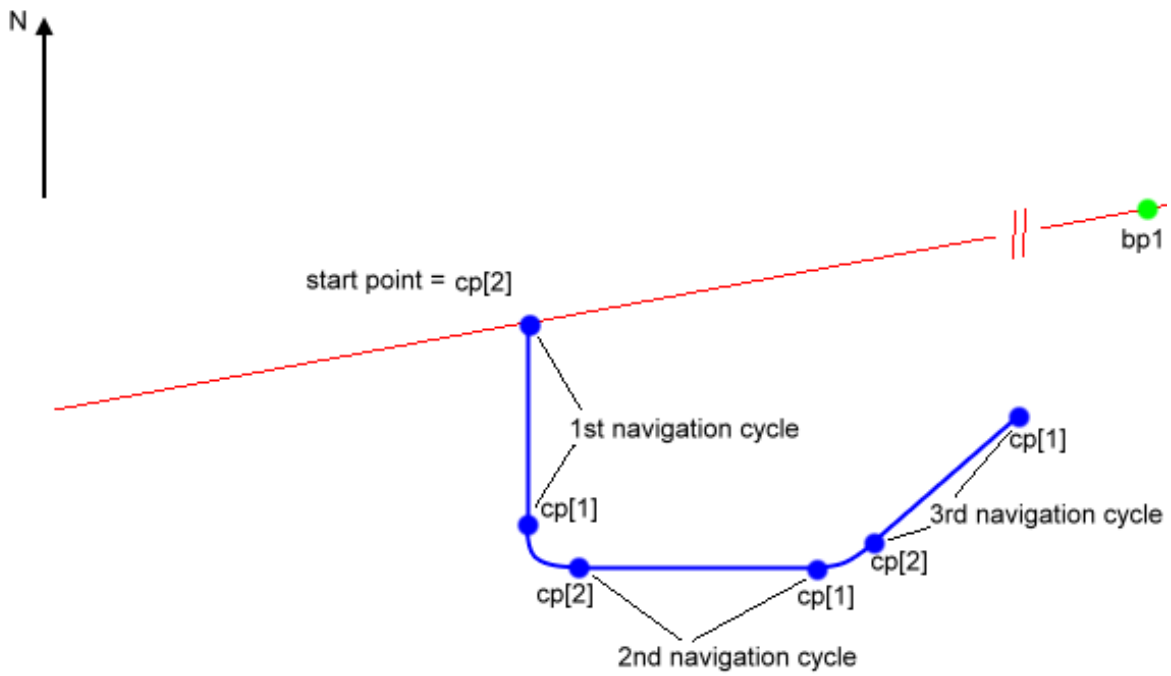


Figure 3.12: *Startup procedure 2 with Cool Robot pointing south*

The function to make course corrections is open loop. That means there is no feedback during the turning itself. This is due to the impreciseness of the bearing information and the lack of a compass (see chapter 3.1). But the open loop correction meets the requirements for our project. What are 10 m on a whole continent of ice?

For the course correction, I measured the time it takes the robot to make a 360° turn while driving the motors on one side at only 90% speed instead of 100% for waypoint following at full speed and one side at 50% instead of 60% for waypoint following at partial speed. That is possible because the motorcontrollers are setup in velocity mode. That means they try to keep the motor at the desired speed by drawing more current.

For example, if the initial bearing to the first active waypoint is 230°, the function calculates an off bearing of -130° without taking the robot‘s current heading into account. The off bearing range is converted from $0° \leq \alpha \leq 360°$ to $-180° \leq \alpha \leq 180°$ with a negative value causing a left turn and a positive value causing a right turn and a bearing is generally measured clockwise. To avoid imprecise turning angles, I limited the maximum turning angle for one

navigation cycle to 90°.

The current position after finishing the turn is stored and parsed into current point[2] for the next navigation run. The robot now travels straight ahead for 30 seconds to start the next navigation cycle with current point[1]. The distance between current point[2] and current point[1] is calculated to determine the current bearing. Traveling with a maximum speed of 1.25 m/s, the distance should be greater or equal 30 m. That is accurate enough for the gps receiver's position data.

Figure 3.13 points out the necessity for basing point generation.

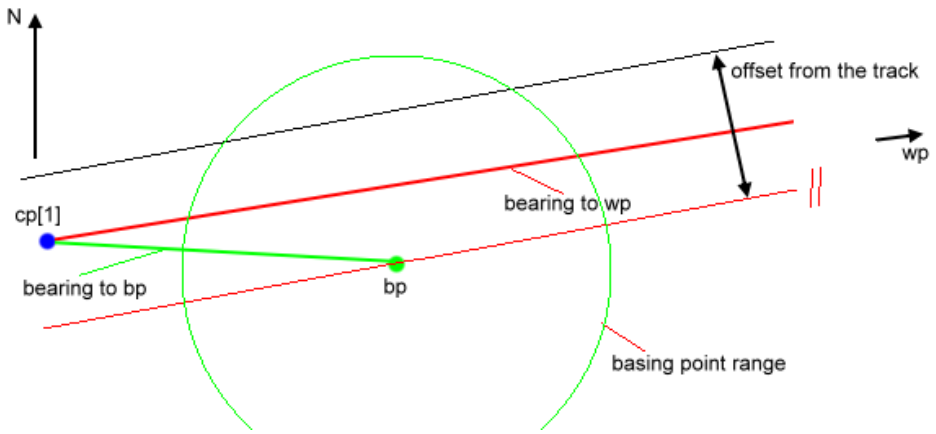


Figure 3.13: *Example startup navigation (drawing)*

The current bearing on navigation cycle 2 is almost equal to the bearing to the active waypoint, but varies from the bearing to the basing point. If the robot would head to the waypoint, no course correction would be made and the robot would travel on a path parallel to the calculated track. With basing points, the traveled path is more predictable because the robot makes more course corrections towards the calculated course. If the robot reaches a distance of less than 20 m to a basing point, the next basing point on the track is generated and the robot follows that new bearing (Figure 3.14).

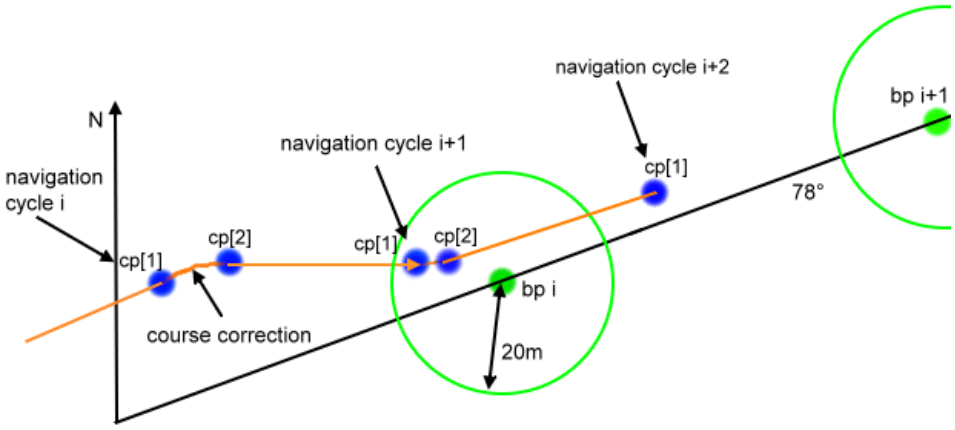


Figure 3.14: *Basing point generating example (drawing)*

3.2.1 Calculating the distance between two gps positions

The function to calculate the distance between two positions was already written, as part of a diploma thesis. But when I first tested the waypoint following or especially the navigation algorithm, with some special values of the two longitudes, a domain error was produced in the "gps_bearing" function. In one example case, the algorithm tried to calculate arccos(-1.238) which is impossible. I figured out that one problem was the "gps_ground_distance" function whose result is used to qualify the bearing. There were two different errors in the "gps_ground_distance" function. The distance was originally calculated by

$$dist = 2 \cdot arcsin(\sqrt{cos(lat_a) \cdot cos(lat_b) \cdot (sin(\frac{lon_a - lon_b}{2}))^2 + (sin(\frac{lat_a - lat_b}{2}))^2}) \quad (3.1)$$

Let me explain the problem considering as example the two positions a and b from the testing on the golf course on jan/11/2005 in dd.mmmmmm (a_{lat}) and in radian (lat_a):

$$\begin{aligned} a_{lat} &= 43.428442^\circ \Rightarrow lat_a = 0.76295445\ rad \\ b_{lat} &= 43.428420^\circ \Rightarrow lat_b = 0.76295381\ rad \\ a_{lon} &= 72.170198^\circ \Rightarrow lon_a = 1.26158792\ rad \\ b_{lon} &= 72.170212^\circ \Rightarrow lon_b = 1.26158832\ rad \end{aligned}$$

whereas radian is $lat_a = (a_{lat.degrees} + a_{lat.minutes}/60)/180 \cdot pi$. In dynamic C the numbers lat_a, etc. are defined as IEEE standard 32 bit floating points.

	Sign	Exponent	Fraction	Bias
Single Precision	1 [31]	8 [30-23]	23 [22-00]	127
Double Precision	1 [63]	11 [62-52]	52 [51-00]	1023

Figure 3.15: *Precision for decimal values*

The range for floats is not a problem, because the exponent is a signed integer in the range of -126 to 127. But if there are no leading zeros, the expansion is rounded off at the 23rd digit after the binary point. Which is equivalent to $\frac{1}{4194304}$ or 2.38419^{-7} . The problem with equation 3.1 is was not that it is false, but that it is not precise enough for our navigation algorithm, because it tries to compensate for not having double precision floats. The fact was, that dynamic C does not provide a data structure with double precision, like C++ or C. A library with a structure with almost double precision was found(see chapter 3.2.3) and I developed the formula for a distance calculation on earth based on spherical coordinates.

For a correct calculation of a distance between two positions on earth, the latitudes and longitudes need to be converted into azimuth and pole angle. To accomplish a range for the azimuth angle (φ) of

$$-180^\circ \leq \varphi \leq 180^\circ$$

and

$$-90^\circ \leq \Theta \leq 90^\circ$$

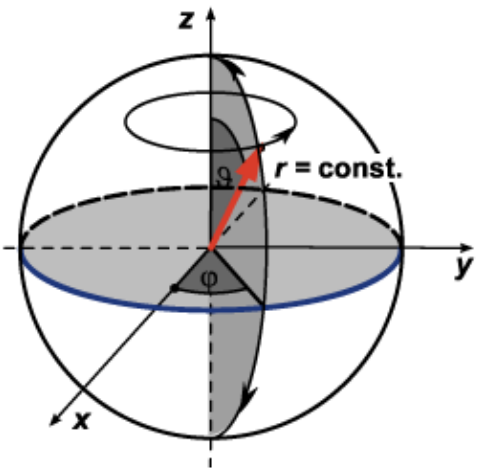


Figure 3.16: *Spherical coordinates*

for the pole angle (Θ), I do the following transformations in the source code:

$$\Theta = \begin{cases} -lat_i & \text{for } direction = \text{`}S\text{`} \\ +lat_i & \text{for } direction = \text{`}N\text{`} \end{cases} \tag{3.2}$$

$$\varphi = \begin{cases} -lon_i & \text{for } direction = \text{`}E\text{`} \\ lon_i & \text{for } direction = \text{`}W\text{`} \end{cases} \tag{3.3}$$

For latitude and longitude on earth, see figure 3.1. With these transformations, every position on earth can be described by

$$f: \begin{pmatrix} r \\ lon_a \\ lat_a \end{pmatrix} \mapsto \begin{pmatrix} r \cdot cos(lon_a) \cdot sin(lat_a) \\ r \cdot sin(lon_a) \cdot sin(lat_a) \\ r \cdot cos(lat_a) \end{pmatrix} = \begin{pmatrix} x \\ y \\ z \end{pmatrix} \tag{3.4}$$

The angle α in radians between two positions on earth then is calculated with the scalar product between the two position vectors:

$$cos(\alpha) = \begin{pmatrix} cos(lon_a) \cdot sin(lat_a) \\ sin(lon_a) \cdot sin(lat_a) \\ cos(lat_a) \end{pmatrix} \cdot \begin{pmatrix} cos(lon_b) \cdot sin(lat_b) \\ sin(lon_b) \cdot sin(lat_b) \\ cos(lat_b) \end{pmatrix} \tag{3.5}$$

$$= cos(lat_a) \cdot cos(lat_b) + sin(lat_a) \cdot sin(lat_b) \cdot (cos(lon_a) \cdot cos(lon_b) + sin(lon_a) \cdot sin(lon_b))$$

The angle α would be easy to calculate by

$$\alpha = arccos(cos(lat_a) \cdot cos(lat_b) + sin(lat_a) \cdot sin(lat_b) \cdot cos(lon_a - lon_b)) \tag{3.6}$$

, but the double precision library does not include an arccos function. So I had to convert the arccos into something known which is the arctan in this case:

$$arccos(\alpha) = arctan(\frac{-\alpha}{\sqrt{1-\alpha^2}}) + 2 \cdot arctan(1) \tag{3.7}$$

The distance then is calculated with the angle converted to degrees and multiplied with the distance between two degrees.

$$dist\,[km] = \alpha\,[^\circ] \cdot \frac{180}{\pi} \cdot 111.136 \left[\frac{km}{^\circ}\right] \tag{3.8}$$

3.2.2 Calculation of gps bearing and off bearing

The function to calculate the bearing between two gps positions "gps_bearing" had to also be transformed for a use with the "_double" precision structure and can be found in the gps.lib. It returns the bearing in true degrees. I took the formula to calculate the bearing with knowledge of the distance between two points a and b

$$bearing \;=\; arccos(\frac{sin(lat_b) - sin(lat_a) \cdot cos(dist)}{sin(dist) \cdot cos(lat_a)}) \tag{3.9}$$

and converted it to use double precision (see chapter 3.2.3). The arccos was substituted again with equation 3.7.

The navigation algorithm calculates different kinds of bearings. The initial bearing is the bearing between two waypoints and marks the desired track for the CoolRobot. Initial distance and initial bearing do not change unless the robot reaches the waypoint and heads to the next waypoint. The bearing to waypoint ("bearing_to_wp") is the bearing from the current position of the robot to the active waypoint, same as the bearing to basing point ("bearing_to_bp") is the bearing from the current position to the basing point. These bearings and the appropriate distances change between two navigation cycles and are used to calculate the off bearing by taking the difference to the current bearing ("curr_bearing"):

$$off\_bearing = \begin{cases} bearing\_to\_wp - curr\_bearing & \text{for } dist\_to\_wp \leq dist\_to\_bp \\ bearing\_to\_bp - curr\_bearing & \text{for } dist\_to\_wp > dist\_to\_bp \end{cases} \tag{3.10}$$

The range for the "off_bearing" is $-180^\circ \leq x \leq 180^\circ$, whereas a negative value corresponds to a left turn and a positive value to a right turn to correct the course.

3.2.3 Double precision floating point in dynamic C

Since the best way to tell the robot‘s heading is to take the bearing between the last two positions while navigating, the single precision floating point is not precise enough for the navigation algorithm. The distance can only be calculated exactly with the angle between two points on earth, measured from geocenter(see chapter 3.2.1). Dynamic C does not provide a structure double. Robert Richter wrote a double precision library on his own. We purchased it from him. The package included the dynamic C library, his C-code, a readme file, an example file and an expression builder. This chapter presents the different functions used for the navigation and the different commands, especially the syntax.

The double precision library creates a data type called "_double", which is internally defined as structurechar Bytes[8]_double . The accuracy depends on the functions used:

Add, subtract, multiply, divide, and square root are all accurate down to the last bit. Add, subtract, multiply, and divide all use 8 bits for rounding with 1 guard bit and 7 sticky bits. Square root only has 5 sticky bits. The transandentals use C code and each term in the series is rounded, so the multiplication and addition can result in two bit error each round. The largest series is arctan with 22 terms, so a total of 44 operations can result in about 5 bits error worst case.

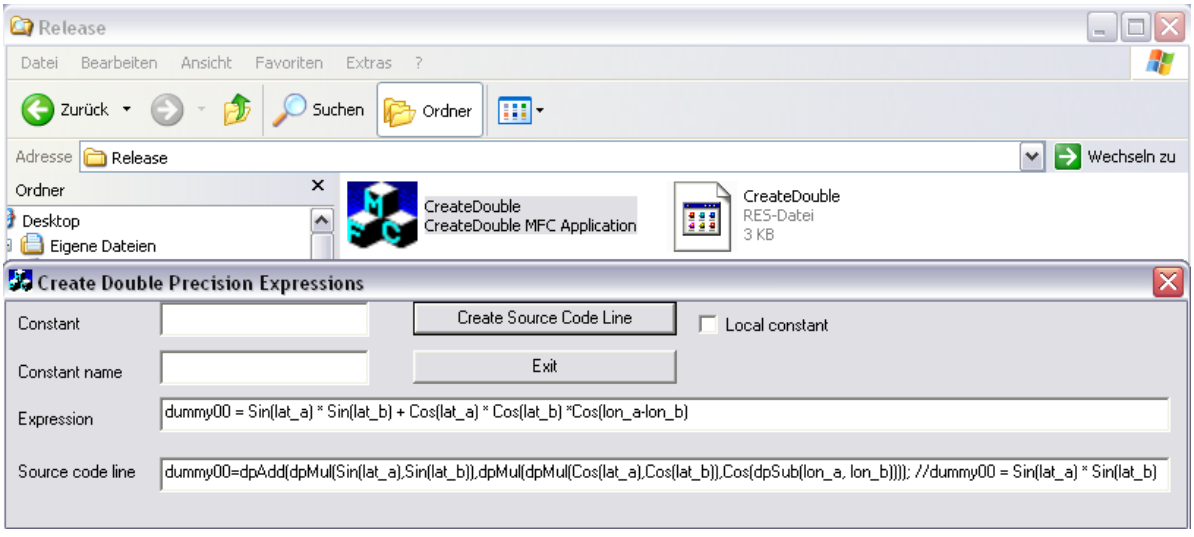


Figure 3.17: *Expression builder for "_double"*

Figure 3.17 shows the different syntax for single float and double precision "_double". The window shows the MFC Application to be started. The Expression builder helps to generate source code for the new structure "_double" with the known syntax from calculations with floats. The expression as programmed for single floats has to be entered in the "expression" line. The expression builder has no button to create the new source code. You have to have the "expression" line in focus and hit the enter key. The translated source code line generated appears in the next line and can be pasted into the desired dynamic C function. The original expression is shown after the double backslash and commented out. The variables "lat_a", "lat_b", etc. can be defined as "_double = lat_a", but there are functions to convert float to double and the other way around. The most important functions are presented here to allow an easy user interface.

_double dpMakeNum(long Num1, long Num2): Should only be used if the source code line is generated with the PC program. This takes two long numbers and takes the bytes in the long numbers and combines them together for the bytes in a double precision number. It is *not* intended to be used to convert long numbers to double

_double dpFloat2Double(float Num): Converts a floating point number to a double precision number. Note that since computers work in base 2 and not base 10, things like 0.1 become 0.1000000014901161. This is an artifact of the base 2 representation, I fill in the missing second byte with zero's, but the zero's in base 2 are not zero's in base 10.

float dpDouble2Float(_double Num): Converts a double precision number back to floating point. This doesn't round, so the last bit may be in error.

_double dpAdd(_double Num1, _doubleNum2): Adds two numbers and rounds the final result. Issues with +/- infinity in the IEEE 754 format are not supported. Also, zero+very small numbers (around $1e-300$) will cause zero to not quite be zero and may result in something like $1.2e-300$. For numbers that aren't at the extremes, however, zero is zero.

_double dpSub(_double Num1, _doubleNum2): returns $Num1 - Num2$.

_double dpNeg(_double Num): Changes the sign of a number

_double dpMul(_double Num1, _double Num2): Multiplies and rounds $Num1 * Num2$

_double dpDiv(_double Num1, _double Num2): Returns $Num1/Num2$

_double dpSqrt(_double Num): Returns the square root.

_double dpSine(_double Angle): Sine of angle in radians.

_double dpCosine(_double Angle): Cosine of angle in radians.

_double dpArctan(_double Angle): Arc tangent in radians.

Let me just give a small example of using the structure "_double":

```
main(){
        _double a, b, c, d, e;
        float print;

        e = dpMul(dpAdd(a, b), dpAdd(c, d)); //e = (a + b) * (c + d)

        print = dpDouble2Float(e);
        printf("result of the _double calculation is: %f", print);
}
```

Table 3.4: *Sample using structure _double.*

This example ought to show the use of the double precision structure which is not supported by dynamic C and is not known to dynamic C as a data type such as float or integer. Variables of "_double" can be defined and used for calculations with the listed and in the "doubleprecision.lib" library written functions. If the user wants to display a number on the screen or transmit a number to a function not listed in the doubleprecision library he has to convert the number to a data type known to dynamic C (chapter 3.4).

3.3 Analog sensors

3.3.1 Power and signal supplies and setup for the ADC evaluation board

The Analog Devices evaluation board eval-AD7490cb is used to read analog signals. The AD7490 is a 16 channel, 12-bit Analog to Digital Converter. The first ADC MAX1231 from Maxim was replaced, because we had problems with the temperature rating for their evaluation board. Any attempt to adapt the cold temperature rated ADC MAX1230, which is the 5V version of the 3.3V MAX1231 failed and support from Maxim was lacking. The second reason for the AD7490 was that it is able to read bipolar signals that are biased at 2.5V. The Maxim part could only read 8 bipolar channels, because it takes true differential readings from two channels. The requirements for a Analog to Digital Converter for our project were not as simple as evidently. The first and most important fact was the cold temperature rating of down to -40°C. The box of the Cool Robot is insulated and the heat of the motor controllers should keep the temperature always above ambient temperature, but this is the maximum rating. The main logic is driven by two microcontrollers, one Mastercontroller for the navigation and control and one Slavecontroller for the power management, which is the work of Alex Streeter´s master thesis. For the navigation and control side, the following analog sensors must be read:

channel	signal	input range
1	motor current A	$-2V \leq V_{out} \leq +2V$
2	motor current B	$-2V \leq V_{out} \leq +2V$
3	motor current C	$-2V \leq V_{out} \leq +2V$
4	motor current D	$-2V \leq V_{out} \leq +2V$
5	motor velocity A	$-1.5V \leq V_{out} \leq +1.5V$
6	motor velocity B	$-1.5V \leq V_{out} \leq +1.5V$
7	motor velocity C	$-1.5V \leq V_{out} \leq +1.5V$
8	motor velocity D	$-1.5V \leq V_{out} \leq +1.5V$
9	tilt sensor roll	$+1.5V \leq V_{out} \leq +3.5V$
10	tilt sensor pitch	$+1.5V \leq V_{out} \leq +3.5V$

Table 3.5: *Analog input channels.*

Most analog to digital converters are not able to handle negative input voltages. So we centered

the output at 2.5V and generated a bipolar input from $0.5V \leq V_{in} \leq 4.5V$. The AD7490 is able to change the input range from 0 to V_{ref} to 0 to $2 \cdot V_{ref}$, where the reference voltage of $V_{ref} = 2.5V$ is provided from an on-board high precision reference. The only problem was that Analog Devices started the production of their evaluation board in February.

The power and signal supply for the ADC and the DAC is made through a 20 wire ribbon cable (Table 3.6).

1	GND (DAC)	DC-DC board
2	+10V (DAC)	DC-DC board
3	SDI (DAC)	PC0
4	-5V (DAC)	DC-DC board
5	CS (DAC)	PB2
6	CLKD (DAC)	PF0
9	VREF (+5V)	rabbit eval. board
16	GND (ADC)	DC-DC board
17	CS (ADC)	PD0
18	CLKB (ADC)	PB0
19	DIN (ADC)	PC4
20	DOUT (ADC)	PC5

Table 3.6: *ADC / DAC ribbon cable.*

The on-board components of evaluation board include a programmable ultra high precision bandgap reference and four ADG467G quad op-amps which are used to buffer the sixteen analog input channels.

The AD7490 evaluation board is build to be used with the Eval-board controller from Analog Devices. When using it with the Eval-board controller, all supplies are provided through the 96 way connector. When using the evaluation board as a stand alone unit, the external supplies must be provided to the alternate pins. For connections of power supplies that are provided to the board for interfacing the Jackrabbit microcontroller on serial port B see Table 3.7.

For using the evaluation board as a stand alone unit, +5V must be connected to V_{DD} to supply the AD7490 and the on-board high precision reference. If interfacing the board with 3V systems, +3V can be connected to the V_{drive} pin. Usually the supply voltages for the op-amps

digital supply voltage V_{DD}	J7
digital ground D_{GND}	J7
analog supply voltage AV_{DD}	J2
analog ground A_{GND}	J2
positive op-amp voltage +10V	J3
negative op-amp voltage -5V	J3

Table 3.7: *EVAL-AD7490CB power supplies.*

are $\pm 12V$, but the supplied voltages of -5V and +10V availablefrom the housekeeping power distribution board on the robot are within the desired range of $-18V \leq V_{neg} \leq -4.5V$ and $+4.5V \leq V_{pos} \leq +18V$. The evaluation board has 19 switch and 19 link options to adjust the desired functions. For operation with the Jackrabbit microcontroller the switches and links have to be set as shown in Table 3.8.

Link No.	Function
LK0-LK15	Adds a 50. termination to AGND at the Ain0 to Ain15 sockets (left unconnected).
S0-S15	Allows to user to connect a particular AD713 op-amp input to ground (H)
LK16	In position "C" an external VDRIVE supply voltage must be supplied via J7.
LK17	In position "A", the AD780 provides the 2.5V reference to the AD7490.
LK18	Adds a 50. termination to AGND at the Vin input to the Bias up circuit (unconnected).
LK19	This link option selects the source of the SCLK input.
S17	In position J2, the +12V is supplied from an external source via connector J3.
S18	In position J3, the -12V is supplied from an external source via connector J3.
S19	In position J2, the AVDD is supplied from an external source via connector J2.

Table 3.8: *Switch and link options on EVAL-AD7490CB.*

3.3.2 12-bit, 16 channel Analog to Digital Converter on serial port B

When setup as described in chapter 3.3.1, the AD7490 can be accessed trough serial port B using SPI.

SPI is a three or four wire connection to shift data between two parts like a microcontroller and an analog to digital converter. There are two connections for data input and data output and then one for chip select and one for the serial clock. A data word transmission is started by generating a falling edge on the chip select line $\overline{CS}$. The following defined number of bits are send with the falling edge of the serial clock SCLK. After the transmission, $\overline{CS}$ is pulled high again to end the data word. Figure 3.18 shows an example conversion request on serial port B.

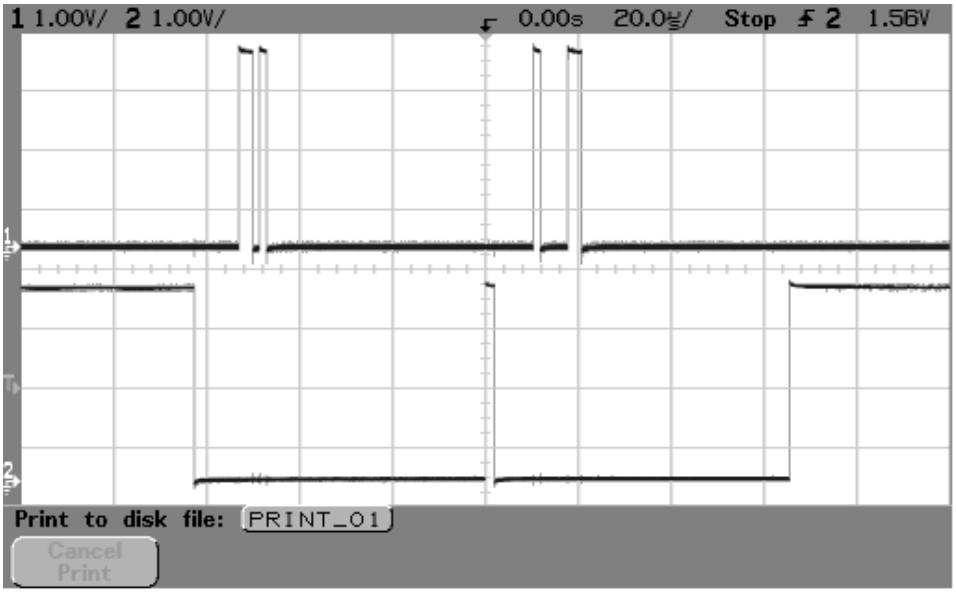


Figure 3.18: *Sample SPI communication on serial port B*

Channel 1 is PC4, the serial data output of the jackrabbits serial port B sending two 16-bit data words and channel 2 is the $\overline{CS}$ being pulled low for the transmission. Logic one is 3.3 V and low is 0 V.

The problem here was, that the microcontroller has four SPI ports, A, B, C and D but dynamic C only provides SPI library code for the use of one SPI port at a time. The desired serial port has to be enabled to transmit data, and with the use of the SPI functions it is not possible to enable more than one serial port. There is the possibilty to change the definition of the SPI port in the function, but the DAC needs a logic high all the time not to update the output value. If the SPI port would be changed to serial port B instead of serial port D for the DAC, the output for all four motors would change to -2.9 V which is equal to a motor speed of -100%.

So I had to rewrite the SPI.lib library into a library called SPI_B.lib to make a simultaneous use of two serial ports possible. It uses the same code but only renamed functions for writing to or reading from a serial port (see Table A.1in App.A). For taking readings from the ADC, the function to write and read data is SPI_BWrRd(command, data, 2). The original SPI.lib is used to interface the DAC to control the brushless dc motors through serial port D.

The AD7490 is a 16 channel, 12-bit analog to digital converter with up to 1MSPS(Mega Samples Per Second) and a 12-bit control register. The control register is a write-only register with the MSB(Most Significant Bit) transferred first. For the data in the control register being transferred on the DIN line at the same time, the conversion result is send out on the DOUT line to the Jackrabbit each control register change is valid from the next conversion only. As every conversion result is a 16-bit data word, it takes 16 serial clock cycles to load the new 12-bit control register data. The 12 control bits are followed by 4 zeros, but only the first 12 bits are loaded to the control register. Figure 3.19 shows the structure of the 12-bit data word loaded to the control register.

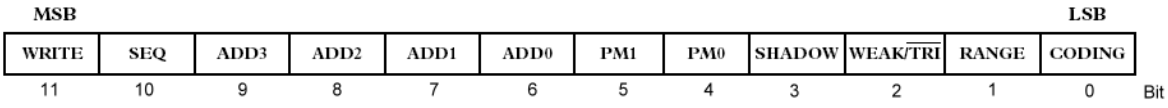


Figure 3.19: *12-bit Control register sectioning*

Write: The Write bit has to be set to 1 to load the following 11 bit to the control register. If set to 0 the register remains unchanged.

SEQ, Shadow: The SEQ and the Shadow bits select one of the four modes of operation of the sequencer. If set to 00, the sequence function is not used and only a conversion on the selected channel is made.

ADD3-ADD0: The four address bits are used to select a channel for the conversion. The four bit word corresponds to the decimal number of the channel (1-16).

PM1, PM0: These two bits select the power mode for the ADC. In normal operation mode

they are set to 11. The ADC runs fully powered and allows the fastest conversion rate.

Weak/$\overline{TRI}$: Selects the state of DOUT after the conversion. For SPI interface this bit is set to 0 and DOUT will return to three-state at the end of the conversion.

Range: The Range bit selects between two analog input ranges: $0 \leq V_{in} \leq V_{ref}$ if set to 1 or $0 \leq V_{in} \leq 2 \cdot V_{ref}$ if set to 0. If the input range of up to $2 \cdot V_{ref}$ is selected, the digital supply voltage must be 5 V!

Coding: Selects the output format for the 12-bit conversion result. If set to 1, the format will be straight binary and if set to 0, the result will be returned in twos complement.

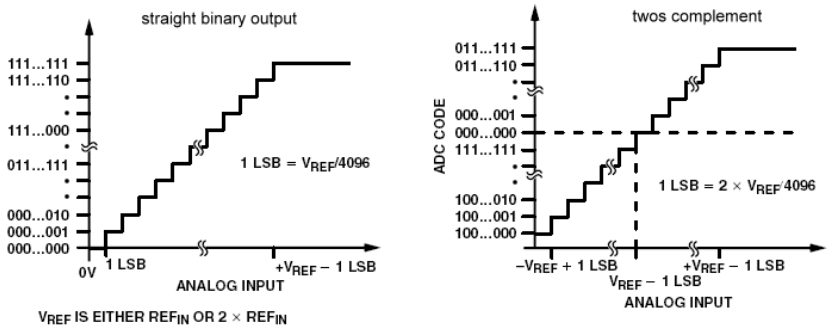


Figure 3.20: *Straight binary vs. twos complement output format*

These two different output formats have a different transfer characteristic for the output value only. An analog voltage on one of the 16 channels is transferred into a 12 bit integer (0...4095). Therefor in both cases, the full scale input range of either 0V .. V_{ref} or 0V .. $2 \cdot V_{ref}$ is divided into 4096 steps. One step is the LSB which has a value of $1LSB = \frac{V_{ref}}{4096}$ or $1LSB = \frac{2 \cdot V_{ref}}{4096}$ depending on the input range. With a 2.5 V reference voltage the LSB has a value of 0.00061V or 0.0012V, which is the maximum error from the real analog input. The output integer is given by $code = \frac{V_{in}}{1LSB}$ for straight binary output (Figure 3.20). Straight binary output is used for single ended unipolar signals, but the motor current and the motor velocity output signals are bipolar, depending on the sense of direction.

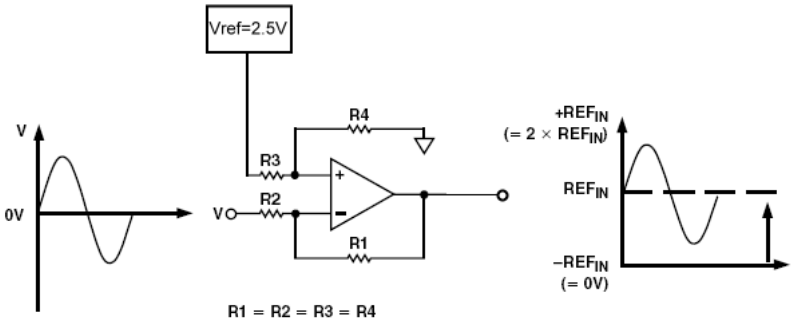


Figure 3.21: *Circuit to bias bipolar signals about Vref*

As the analog to digital converter cannot handle negative inputs, the signals have to be biased about V_{ref}. The negative full scale -2.5V is 0V and the positive full scale +2.5V is +5V. A general circuit to bias up a bipolar input at about 2.5 volts is given in Figure 3.21. The analog input conditioning circuit we use in our case is presented in Appendix C.

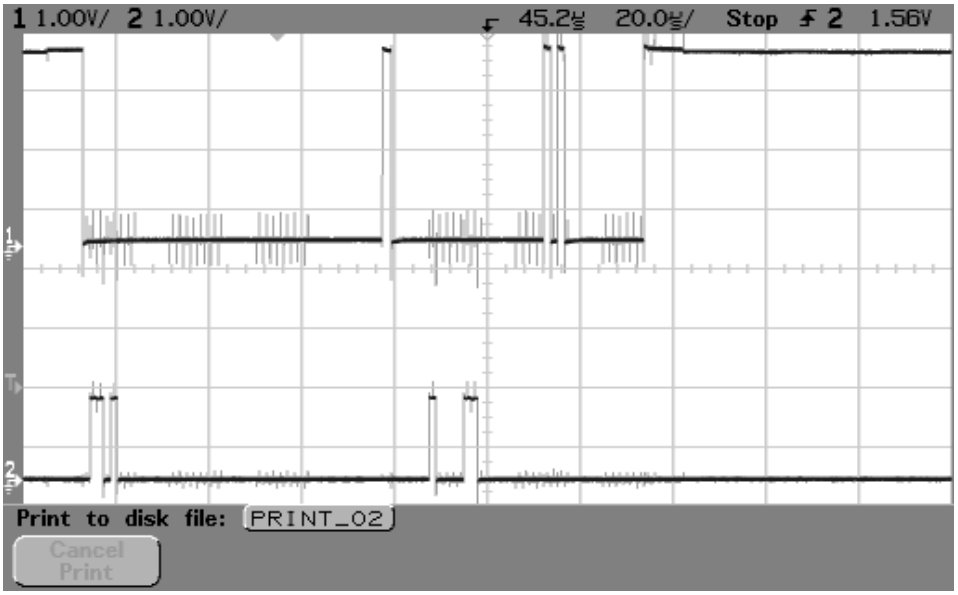


Figure 3.22: *ADC DIN and DOUT with analog input signal*

The DOUT line of the AD7490 shifts a 16-bit data word to the serial port B. The first four bits indicate the information on the channel on which the conversion was requested. The next 12 bits are the digital value of the analog input voltage. The SPI port reads the 16-bit data word

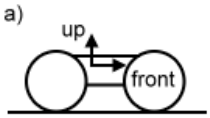
as two complete bytes which are shifted into a two dimensional character array "data[2]". A bitwise "and" is performed with the first byte and "0F" to extract the four address bits:

$$0000\ 1111\ \&\ 0101\ 0011\ =\ 0000\ 0011 \tag{3.11}$$

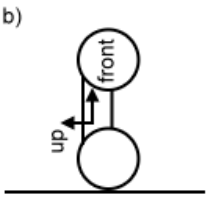
The first four bits of the digital conversion result remain unchanged. At first, I thought about programming a checksum for the address bits, to guarantee a reading on the correct channel, but then decided to keep it simple and the communication through the serial port is correct.

3.3.3 Dual axis accelerometer used as a tilt sensor

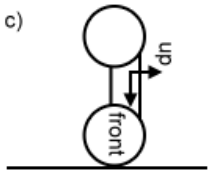
The dual axis tilt sensor is a dual-axis accelerometer "ADXL203" from Analog Devices. The ADXL203 measures acceleration with a full-scale range of $\pm$1.7g. The ADXL203 can be either used to measure dynamic or static acceleration(e.g.,gravity). By mounting different capacitorsC_x and $C_y$to theX_{out} and Y_{out} pins, the user selects a bandwith between 0.5 Hz and 2.5 kHz of the accelerometers. The part is temperature rated from -40°C to +125°C. With a 5V supply voltage, the accelerometers have a sensitivity of $1000\frac{mV}{g}$. The five extremal positions are listed and shown below.



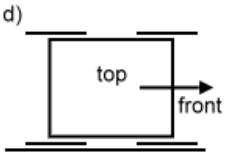
$$x_1 = 2.5V\ ; y_1 = 2.5V\ ; x_2 = 2.5V\ ; y_2 = 1.5V$$



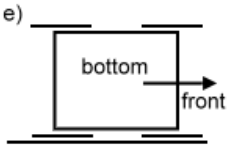
$$x_1 = 3.5V\ ; y_1 = 2.5V\ ; x_2 = 1.5V\ ; y_2 = 2.5V$$



$$x_1 = 1.5V \; ; y_1 = 2.5V \; ; x_2 = 3.5V \; ; y_2 = 2.5V$$



$$x_1 = 2.5V \; ; y_1 = 3.5V \; ; x_2 = 2.5V \; ; y_2 = 2.5V$$



$$x_1 = 2.5V \; ; y_1 = 1.5V \; ; x_2 = 2.5V \; ; y_2 = 2.5V$$

The accelerometers are used for the CoolRobot to detect a maximum pitch or roll angle to prevent it from tipping over if driving while climbing large sastrugi features. An accelerometer has a varying sensitivity in the range of -1g to +1g. The output changes with nearly $17.5\frac{mg}{\circ tilt}$ when the accelerometer is perpendicular to gravity but the resolution decreases and the output changes at only $12.2\frac{mg}{\circ tilt}$ at 45°. The analog output voltage $V_{out} : \; 1.5V \leq V_{out} \leq 3.5V$ is converted to a range between $-1V \leq x_{out} \leq +1V$ in the function "read_sensors()" written in the "analogin.lib" library. With $1V \Leftrightarrow 1g$ the output tilt in degrees can be calculated as

$$pitch = arcsin(\tfrac{x_{out}}{1g}) \tag{3.12}$$

$$roll = arcsin(\tfrac{y_{out}}{1g}) \tag{3.13}$$

One thing to keep in mind is, that both outputs can exceed the output range of -1V to +1V due to vibration or shocks by falling down a steep and sharp edge of a snow feature. To prevent a domain error when trying to calculate the $arcsin(x)$ for $x > 1$, I round the output ranges off to 1 if they are larger. At 45° tilt, which is the stalling angle x_{out} or y_{out} has a output of$\approx 0.707V$, defined as the critical tilt value (see chapter 3.3.6). To reduce the influence of vibrations on the outputs x_{out} and y_{out} of the tilt sensors, a 2^{nd} order Butterworth Filter acting as a lowpass is integrated in the circuit. The bandwidth then is given by

$$BW\,(Hz) \;=\; \frac{1}{2 \cdot \pi \cdot \sqrt{2} \cdot R \cdot C} \tag{3.14}$$

with $R \;=\; 22k\Omega$ and $C \;=\; 0.1\mu F$, we have a bandwidth of 51 Hz. At frequencies higher than 51 Hz, the attenuation is $-40\frac{dB}{dec}$. The specific feature of a Butterworth Filter is, that it has only one cut-off frequency.

3.3.4 Motor current and motor velocity sensors

Eyes and ears of the Cool Robot, that is a good transcription for the analog sensors and especially for the motor currents and the motor velocities. The Cool Robot is powering all four motors in velocity mode. The AMC brushless servo amplifiers try to keep the motors at the desired revolutions by increasing the current draw for each motor if it has to provide more torque. In reality, it is not possible to keep the revolutions at the exact same level. If the Cool Robot climbs a sastrugi feature for example, not all wheels will reach the inclination at the same time and one wheel has to produce more torque than the others. As a result, the current draw for that motor increases to keep the revolution up. Meanwhile the revolutions for that wheel drop a little and not seeing the Cool Robot or the feature that is faced, one can easily guess what the current terrain looks like. The other way around the motor current and motor velocity sensor for one wheel can also detect a wheel not in contact with the snow. The Cool Robot will be confrontated with driving with one wheel in the air frequently, so that this will not be an extreme case. But we want to be able to tell if the Cool Robot is high centered on a large sastrugi feature or a very firm accumulation of snow with two or more wheels not in contact with the snow.

Another reason for the motor current sensors is the very firm energy budget. The Cool Robot

is powered by solar energy, which is a very constant and stable energy source when the sun is shining. There will never be "too much" energy and if there is a surplus of power, then it is nice to know for the next generation of Cool Robots. Logging the motor currents gives a very important and highly interesting information on rolling resistance on the snow in Antarctica and will be useful for further expeditions.

Both sensors are provided by the AMC brushless servo amplifier on the connector P1. The current monitor output is connected to pin8 and the velocity monitor output is conncted to pin15. The current monitor output is a voltage scaled by the factor two for each ampere current draw (1V = 2A). A positive voltage tells the user that the dc brushless motor is turning clockwise and a negative voltage counter clockwise. The current monitor output is always within a range of $-2V \leq V_{curr} \leq +2V$ due to the set current limit of the motors.

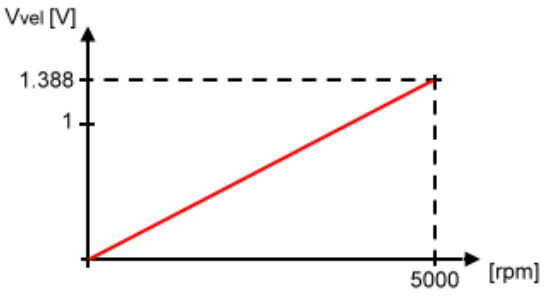


Figure 3.23: *Velocity monitor out vs. motor revolution*

The velocity monitor output is a periodic voltage with a rising offset for an increasing revolution. The output scales with 1V per 120 Hz Hall frequency. At a maximum revolution of 5000rpm and a number of four poles, the maximum velocity monitor output voltage is:

$$V_{vel} = \frac{5000rpm}{120Hz \cdot 60sec} \cdot 2 \cdot 1V = 1.388V \tag{3.15}$$

3.3.5 Function to process the sensor data

It is one part to adjust the range for an analog signal, to build the conditioning circuits and make the correct connections. But reading out the analog to digital converters output is another. This section describes the data processing from the 12 bit integer value to the corre-

sponding output voltage or current. The target is to have an output value which is comparable to a multimeter. Each signal has an input range from 0V to +5V because each analog sensor is connected to the conditioning board. But the different functions of the sensors have to be scaled differently to get the desired output.

The analog sensor readings are programmed in the function "read_sensors()" in the analogin.lib. The 16 output channels are read with the function "ReadAD". The 12 bit return value is an integer between 0 and 4095. Each integer corresponds to a voltage or current. By multiplying with a scale factor, each output can be adjusted separately. Each scale factor has to convert the integer to the chosen input range for the ADC of 5V by $voltage \; = \; output\,[i] \cdot \frac{5}{4096}$. Then each scale factor for the analog sensor‘s output has to be multiplied. For the motor current that is 2, because the output is 1V for 2amp motor current. The motor velocity output is 1V for 120Hz Hall frequency and the tilt output is 1V for 1g. The final output values are given below.

$$\begin{aligned} motor\ current\,[A] &= \tfrac{5}{4096} \cdot 2 \ \cdot int_{value}\,[A] \\ motor\ velocity\,[RPM] &= \tfrac{5}{4096} \cdot \tfrac{120 \cdot 60}{2} \ \cdot int_{value}\,[RPM] \\ tilt\ angle\,[^\circ] &= \tfrac{5}{4096} \ \cdot int_{value}\,[^\circ] \end{aligned} \tag{3.16}$$

Used in the interrupt function are the output[0] to output[3] for the motor currents, output[4] to output[7] for the motor velocities and output[8] and output[9] for the tilt pitch and roll.

3.3.6 Sensor interrupts

One of the two different interrupts in the drive mode "wp_follow_full" and "wp_follow_partial" are the sensor interrupts. A sensor interrupt is a jump out of the current drive mode to the manual operator mode or the high centered drive mode for example. A sensor interrupt is produced, when the range of a sensor is exceeded and the mobility of the Cool Robot is no longer guaranteed.

The sensors of the robot are its eyes and all the senses it has. Two different functions are programed for the "sensor range" handling:

1) sensor_high_centered(int *tm_hc, int *wheel_air)

2) sensor_range()

Table 3.9: *Sensor range handling functions.*

Every sensor is read once every second. The tilt sensors for roll and pitch are compared to a limit of the value of "tilt_lim". If the absolute value for one of the tilt sensors exceeds 45° degrees for example, the function stops the robot. A routine to drive the robot back on the driven track is called. The motor speeds are set to backwards 100%. After 4 seconds, it makes a right turn with 90% speed compared to 100% for 18 seconds which is equal to a 60 degrees turn. After that the robot will stop and continue with navigating at the desired speed. If called from drive mode "wp_follow_full" (drive_mode = 1) the motor speeds are set to 100% and if called from "wp_follow_partial" (drive_mode = 2) the motor speeds are set to 60%.

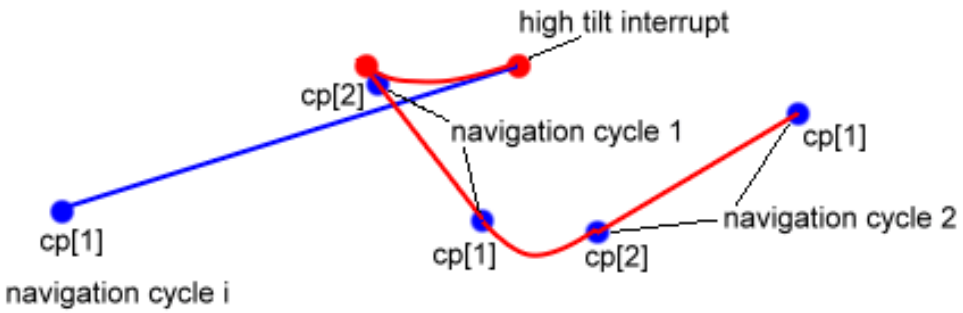


Figure 3.24: *High tilt angle interrupt handling sample*

Figure 3.24 shows the track of a high tilt angle interrupt. After the motor speeds have been set to the speed before interrupted the navigation algorithm will start over again.

The second function checked once every second, is detecting a high centered position. In case

of one wheel being without contact to the snow, the current will drop to the no-load-current value. The motor velocity will increase a little to almost the maximum revolutions. That only is not a criterion to detect a high centered position, because the Cool Robot will travel with only three wheels in contact to the snow repeatedly. What I am doing is, i check all four wheels once every second for a current value that is close to the no-load current value. If that is the case, I check the motor velocity as well. If the motor velocity is above 4950 rpm , I log the tilt angles. The number of the wheel is stored and this wheel is checked again after a second. If the current is still low and the revolutions at a high level, the tilt angles are read out and compared to the first reading. After 10 readings of a very low current, a high speed and almost no difference in the tilt angles the drive mode "high_centered" is called. In the case that the current for the selected wheel increases to the next second, the algorithm recognizes that and all four wheels are checked again. The drive mode "high_centered" is not implemented yet. It is very hard to tell the best way how to get back enough propulsion for further movement. That has to be a part for the next students. The time the robot waits after defining a high centered position is set to 10 seconds but can be adjusted by "tm_hc".

Chapter 4

The overall control unit

The overall control unit of Cool Robot is one main part of the robot's logic. It consist of the Digital Analog Converter TLV5614, four Advanced Motion Controls brushless servo amplifier AMC BE15A8-H and EAD brushless dc-motors EAD DA23gbb-m300. The control unit basically consists of the different drive modes for the Cool Robot. A drive mode calls the navigation algorithm, checks the sensors, and listens for manual interrupts incoming through the user interface radio or iridium modem. Depending on the drive mode the propulsion has to be assured. Each drive mode checks the motor_speeds at frequent intervals and if needed updates the DAC‘s output. The motor controllers are supplied with 48 Volts, as well as the motors themselves. The speed of each motor is controlled with the DAC‘s output. This chapter will explain the design and construction of the DAC setup together with the motor controller. The DAC is connected to serial port D. Table 4.1 shows all serial port connections on the jackrabbit.

serial port:	function
A	programing and compiling port
B	analog to digital converter AD7490
C	GPS-receiver Motorola Oncore M12+
D	digital to analog controller TLV5614
E	radio modem
F	iridium modem

Table 4.1: *Serial port connections and functions for RCM.*

4.1 Navigation and control mode overview

Table 4.2 summarizes the navigation and control modes assumed for the robot.

wp_follow_full	The Cool Robot drives at the top speed of $1.2\frac{m}{sec}$ and navigates autonomously to follow the given waypoints and the generated basing points. The GPS-receiver is set to output the NMEA-GPRMC message once every second. The robot will parse its position once every 30 seconds after achieving the last course correction to calculate the current bearing and the next off bearing. While traveling, the analog sensors are read once every second. The wheel speeds and motor currents are compared to detect a high centering position and switch to the drive mode "got_stuck". The tilt sensors are also interrupt driven to prevent the robot from tipping over.
wp_follow_partial	The same routines as in the drive mode "wp_follow_full" are run, except that the robot travels with a speed of 60%.
manual_operator	The Cool Robot is not navigating autonomously. The GPS-data string send out to the serial port and the motor speed command to the DAC in percent are send back to the radio modem connected to the Laptop and are displayed in the "HyperTerminal" window. The robot can be controled with the keypads: **w** (10% motor speed increment) **s** (10% motor speed reduction **a** (left turn with 10% difference in motor speeds left to right) **d** (right turn with 10% difference in motor speeds right to left) **q** (stop: decreases all motor speeds to zero within 1 second) **p** (switch to wp_follow_full: motor speeds set to zero!)
high_centered	This drive mode is accessed, when the wheel speed sensors and the motor currents create the interrupt in one of the waypoint following drive modes.The Cool Robot tries to get all four wheels back in contact with snow. This routine has to be evaluated during the testing in Greenland.

charge cycle	The navigation is reduced to parsing the GPS Position from the GPS-data string. The motor controller are shut down and the power consumption is reduced to a minimum. Accessed by the Slave controller maintaining the power overall power supply as a part of Alex Streeter‘s master thesis.
high_wind	The robot is turned with one corner facing the wind. Energy consumption is reduced to minimum in case of a blizzard. Movement of twice the length of the robot once in a while to prevent snowing in. Not implemented at this time.
stat_get_data	The drive mode in which the robot mainly does nothing. The largest part of the bandwidth is reserved for the payload data transmission.

Table 4.2: *Control and drive mode overview*

The main control algorithm for the Cool Robot is split into different drive modes. A drive mode is the summarization of the basic functions needed to handle the current situation. As the circumstances change during the robot‘s trip, the priority for each algorithm changes.

The main active program on the Master controller maintains the connection to either the radio modem or the iridium modem (see chapter 5) and also changes the drive modes if needed (see chapter 4.4). More drive modes are designated but not implemented yet, because the needs for the scientific payload are not specified and the wind speed sensor is not implemented yet (see chapter 4.4).

4.2 12 bit Voltage output DAC with serial interface

Selected for our drive train was a Digital to Analog Converter from Texas Instruments, because they had the best support with their package. The digital supply voltage is separated from the analog side and can be varied between 2.7V and 5.5V. The TLV5614 has 4 DAC´s with a resolution of 12 bit and an output voltage. A 12 bit resolution says, that a voltage range, here

the output voltage is divided into $2^{12} = 4096$ steps.

The smallest part each voltage step differs from the next is the LSB(Least Significant Bit) $= \frac{1}{4096} \cdot (voltage range)$. Supply voltage for the part is $\pm$ 5V. VREF is set to 10 V. The DAC is connected to serial port D on the Jackrabbit main controller (for connections refer to Table 3.6). The four DAC's are easily accessable through a 3 wire serial interface (SPI) using the provided code for the SPI.lib. If there is only one device connected to the serial port, $\overline{CS}$ can be tied low. The maximum serial clock frequency for the TLV5614 is 20 MHz. The FS pin is the Frame sync input pin. A falling edge has to be generated on this pin to shift the data in the serial output to the DAC, where the minimum high-level digital input voltage for $DV_{DD} = 5V$ is 2.2 V and the maximum low-level is 0.9 V . The falling edge on FS starts shifting the 16-bit data word, with the MSB(Most Significant Bit) first to the internal register of the DAC clocked by the 16 falling edges of the serial clock. After FS rises or the sixteen bits have been shifted, the addressed DAC updates the output. The data consists of four control or address bits followed by the 12-bit DAC value. DACA, which is addressed by 0000, controls the output voltage for motor A for example (see the drive.lib header for all address bits).

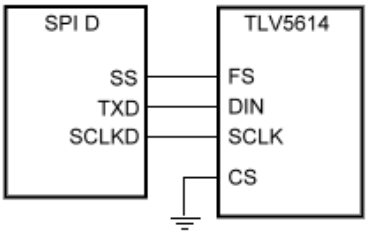


Figure 4.1: *SPI Interface*

D15	D14	D13	D12	D11	D10	D9	D8	D7	D6	D5	D4	D3	D2	D1	D0
A1	A0	PWR	SPD	New DAC value (12 bits)											

X: don't care
SPD: Speed control bit. 1 → fast mode 0 → slow mode
PWR: Power control bit. 1 → power down 0 → normal operation

Figure 4.2: *DAC 16-bit data word*

Each DAC's output voltage then is represented by

$$V_{out} = 2 \cdot V_{ref} \cdot \frac{DAC\ value}{4096}\ [V] \tag{4.1}$$

where $V_{ref} = 2.5V$ in our case and the DAC value the 12-bit data word to be transfered in a range from $0 \leq x \leq 4095$ is. The reference voltage can be adjusted from $0V \leq V_{ref} \leq 3.3V$

with the potentiometer on the DAC board. To buffer the DAC‘s ouput signals, we connected an Opamp LM248 to the output channels.

The final output voltage range is outlined in Figure 4.3.

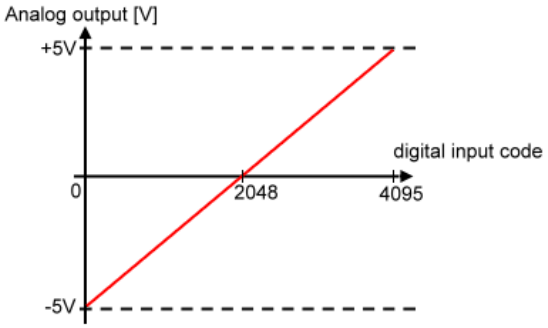


Figure 4.3: *Voltage output vs. digital input*

4.3 AMC brushless servo amplifier and EAD brushless dc motors

The motor controllers are PWM (Pulse Width Modulation) servo amplifiers of the model AMC BE15A8-H. Supplied with 48V, the amplifier can be interfaced with a digital controller or used as a stand alone unit. The amplifier is controlled by the quad voltage output DAC from Analog Devices. Various switches and potentiometers allow the user to adapt the amplifier to the existing system and to synchronize the four amplifiers.

The four switches are set up for velocity mode with the parameters to adjust with the potentiometers.

The function of the four 14-cycle potentiometers are outlined below:

Pot 1: This potentiometer adjusts the loop gain in velocity mode. The loop gain increases while turning clockwise. For the Cool Robot it is turned fully clockwise.

Pot 2: This potentiometer adjusts the current limit. Both continuous and peak current can be adjusted up to the maximum ratings of 7.5A for the continuous current and 15A for the peak current. The peak current limit is always double the continuous limit and at maximum when fully clockwise

Pot 3: This potentiometer adjusts the reference gain. This means the ratio between input voltage from the DAC and output velocity is increased by turning the potentiometer clockwise. Not every amplifier is turned fully clockwise for the Cool Robot, because due to production differences or load differences the general reference gain limits are not at the same level.

Pot 4: This potentiometer adjusts the offset for the input signal and is used to offset any imbalance in the input signal or in the amplifier. It is important that DIP switch 4 is in position "Off" or offset.

The potentiometers are set to produce a maximum revolution of 5000 rpm with a $\pm 3V$ input voltage from the DAC‘s. To assure that all four wheels are at the same revolution speed at the different speeds, the motor controller with the lowest reference gain at full speed has to be taken as a reference. The offset potentiometer has to be turned so that all motors start turning at the same input voltage in both directions. Due to static friction, roughly 20% of input voltage must be commanded before the motors start turning. Then the reference gain for each motor has to be adjusted at full speed in both directions to the reference wheel. Only this guarantees a perfect straight track for the Cool Robot (Figure 4.4).

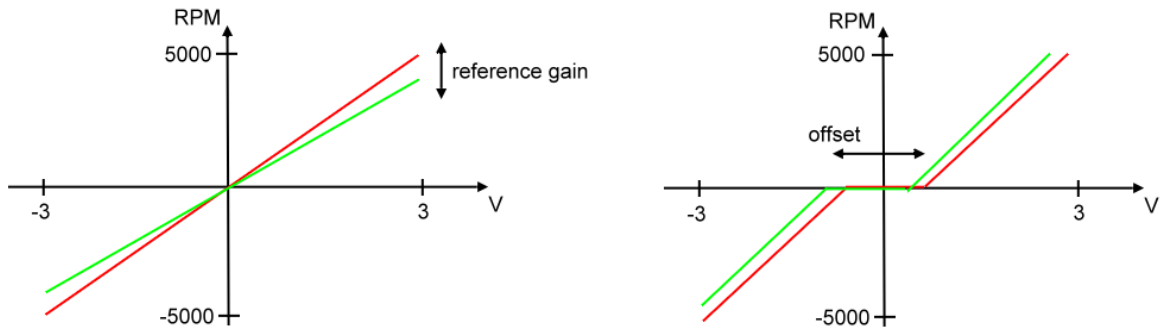


Figure 4.4: *Motor revolutions vs. input voltage*

As shown in Figure 4.4 the output voltage is not linear to the wheel speed. The drawing on the right side shows how the motor speed behaves compared to the input voltage provided from the DAC.

The brushless dc motors DA23-DBB-M300 from EAD-Motors are mounted to the gearhead with a 100:1 ratio. A maximum revolution after the gearhead of 50 rpm and a tire diameter of 20 inch provides a top speed of

$$V_{max} = \frac{50rpm}{60sec} \cdot 2 \cdot \pi \cdot \frac{10inch \cdot 2.54m}{100} = 1.33\frac{m}{s} \tag{4.2}$$

4.4 The different drive modes of Cool Robot

On the trip over the Antarctic Plateau the Cool Robot has to face many different situations. Some algorithms and functions have a different priority during the trip. The best example is the navigation algorithm. Most of the time the Cool Robot will be following waypoints on the Antarctic Plateau, but if the power budget runs low the robot has to stop to recharge the li-ion batteries. Once standing at one position without driving the motors, there is no use of calculating distances and bearings. The navigation algorithm can be "shut down". To meet the different requirements, drive modes for the Cool Robot are implemented. A drive mode grades and arranges the different base functions used to read the sensors, to control the motors or to navigate for example. A detailed overview over the Cool Robot‘s drive modes is given in Table 4.2.
The drive modes and a general description are listed below.

wp_follow_full(): In the drive mode "waypoint following at full speed" the robot travels at $1.3\frac{m}{sec}$ on the calculated track to the next active waypoint. High energy consumption.

wp_follow_partial(): Called from the drive mode "waypoint following at full speed" when the Slave microcontroller sets a power limit which forces the motors to run slower. Still heading to the waypoint.

manual_operator(in_string): Designed to have easy manual control over the robot to drive

it into a garage instead of carrying it. Highest priority and interrupt driven in all other drive modes. Control via keypad (w-faster, a-left, s-slower, d-right, q-stop).

high_centered(in_string): Detected and called by the motor current and motor velocity sensors if the Cool Robot is high centered. A routine that turns the wheels forward, backward, turns left at -100% and +100% to get the Cool Robot unstuck again.

charge_cycle(): Accessed only from the drive mode "wp_follow_partial" if the power budget allows no further propulsion. Parameters have not been selected at this point and need to be set by the Slave microcontroller appropriate for the energy consumption.

high_wind(): A drive mode that has to be implemented once the wind speed sensor is attached. Will turn the robot into the direction of the wind at high speeds ($\geq 20\frac{m}{sec}$. Should prevent the robot from tipping over because it is facing the wind from the side or being tilted at one corner so that the wind is able to get under the robot. Should also move the robot a few meters to prevent it from getting snowed in.

stat_get_data(): The Cool Robot has a scientific assignment. To take measurements it has to stay on one position. In that case the bigger part of the bandwidth of the iridium communication is reserved for the payload for example.

4.4.1 Waypoint following at full speed

The drive mode "wp_follow_full" is the main drive mode for the Cool Robot. In the best case, the Cool Robot only exits this drive mode for stationary data acquisition. Unfortunately there are factors which force the Cool Robot to exit that drive mode. On the Antarctic Plateau very high wind speeds are not uncommon. In that case the robot wants to take a position in which one edge faces the direction of the wind to provide the smallest working surface. One other reason for switching to a different drive mode such as waypoint following at partial speed could be a power limit. However, the Cool robot starts in drive mode waypoint following at full speed after powering up in manual drive mode.

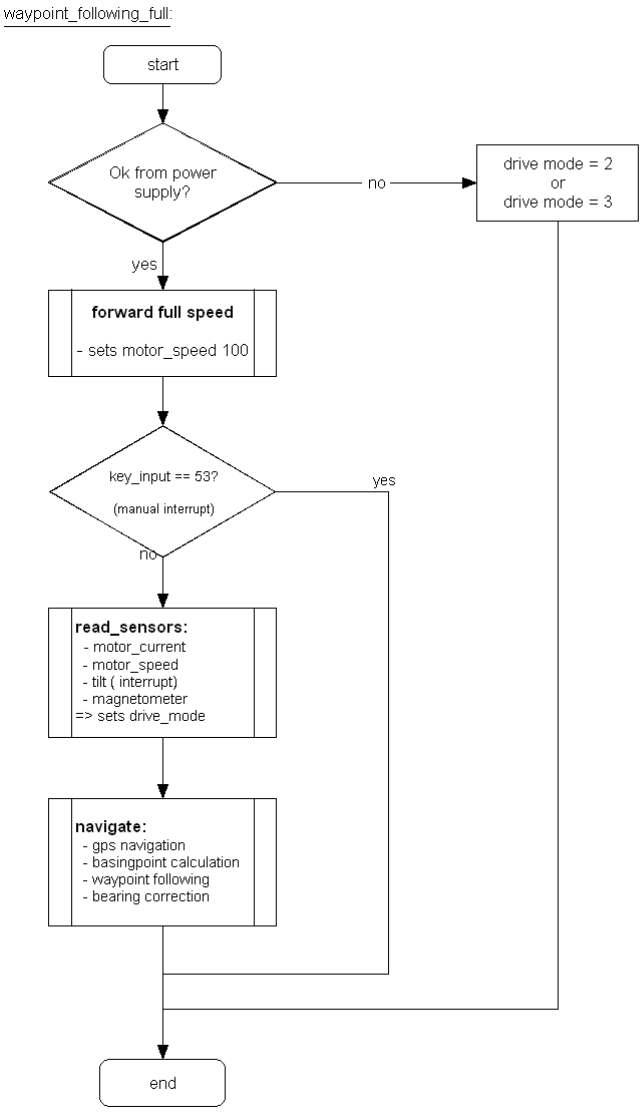


Figure 4.5: *Flowchart of drive mode waypoint following at full speed*

I wanted to keep the structure for the drive modes simple and easy, so that the next users are able to add drive modes that have to meet different restrictions using the basic functions. The basic functions are summarized in Table A.1(App.A).

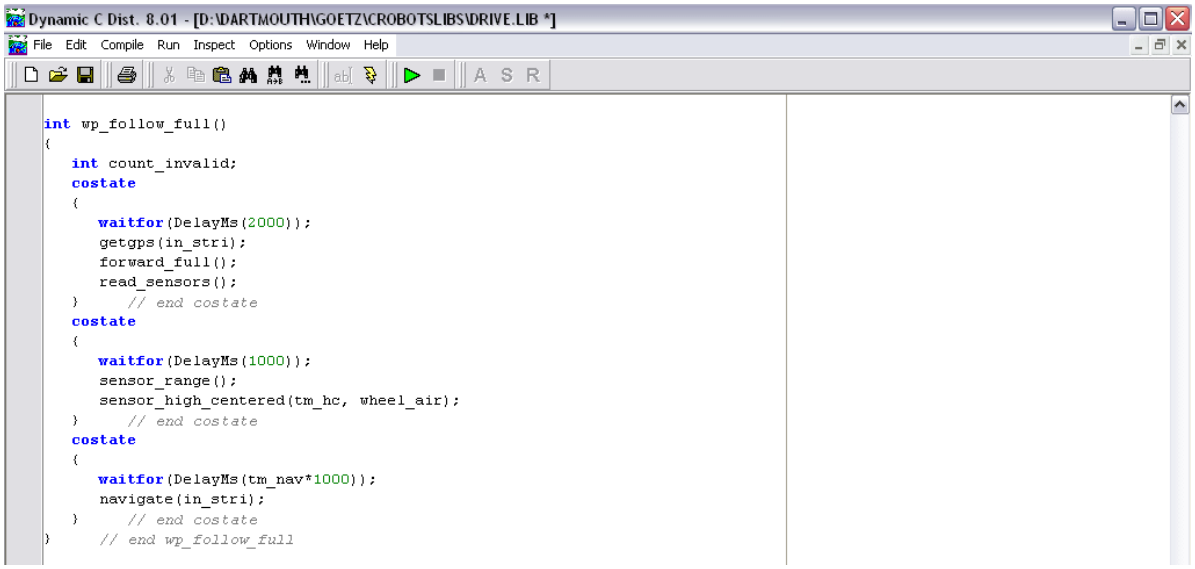


Figure 4.6: *Screen shot of dynamic C code for waypoint following at full speed*

Figure 4.6 shows a screenshot of the function "wp_follow_full" which is written in the drive.lib is called directly from the main program. Once called it is executed in an endless loop if not interrupted. Two kinds of interrupts are build in, interrupts driven by the main program, e.g., the interrupt to switch to manual operator drive mode and interrupts driven by the analog sensors, e.g., a tilt angle higher than 45 degrees. For interrupts from main program, see chapter 5.3.4. and for interrupts from the analog sensors see chapter 3.3.6. The structure of costate tries to imitate multi tasking. The first costate is executed but the stops at the function "DelayMs" which prevents further execution of the costate until the time listed in milli seconds has elapsed. If not, the second costate is executed and so on. Once running, the three costates produce a time delay for an execution of the commands listed behind each costate. In this case, the GPS-data string from the Motorola GPS-receiver is read, the motor speeds are checked if at full speed and the analog inputs are read once every two seconds. The interrupts for high tilt or a high centered position are checked once every second. Then, after the defined navigation cycle time "tm_nav" (30 seconds) has elapsed, the navigation algorithm is called. The robot will now parse its current position, correct the course if necessary and will return back to the

main loop after that.

The drive mode "wp_follow_full" sets the paramaters for the navigation based on GPS-data. It defines the distance between two navigation cycles which has to be aligned with the desired precision, the available GPS-precision and the distances to travel. If the robot navigates once every 10 seconds it will make a lot of course corrections and the track will look like a sawtooth. If the time between two navigation cycles is larger then 30 seconds for example, the algorithm will smooth the track by taking shifts in bearing caused by the terrain into account.

The drive mode also includes the only obstacle avoidance of the robot: high tilt angles. The terrain in the Antarctica is mostly flat and obstacles like mountains or crevasses can be detected on satellite images. The waypoints given to the Cool Robot force it to avoid these obstacles. The sastrugies sculpted by the wind have to be handled. Therefor we have the tilt sensors. The slow speed of the robot allows us to stop it, back it up and drive around the feature if it would be dangerous to climb it.

During waypoint following at full speed, the robot checks the tilt angles , the motor speeds and the motor velocities once every second. If one of them is out of the range, the robot is stopped and the drive mode is changed. After driving around a high tilt angle or after getting out of a high centered position, the robot will start the drive mode "wp_follow_full" again. The same routine as described for the startup is executed to get back on the defined track (chapter 3.2).

During the whole time the robot is driving in "wp_follow_full" it can be interrupted and switched to the drive mode "manual_operator" by sending the command "$CRCMDMANDM" from the modem (chapter 5.3.4).

4.4.2 Waypoint following at partial speed

The drive mode "wp_follow_partial" is implemented to guarantee a movement if the energy budget does not allow to drive the motors at full speed. The motors are driven at 60% of the maximum speed which is equal to a speed of $0.78\frac{m}{sec}$. The drive mode will be called by a routine from the Slave microcontroller which handles the overall energy consuption and bud-

get. The main algorithm is the same as described in chapter 4.4.1. The difference to waypoint following at full speed is, that the time between the navigation cycles is defined for two different situations. If the drive mode is accessed through power restrictions, the navigation time is set with "tm_nav_low" which is longer than in waypoint following at full speed, because the robot needs more time to travel the same distance. The same shape of the track should be achieved. To have the same distance between current position[1] and current position[2], "tm_nav_low" is calculated automatically to

$$tm_{nav\,low}\,[sec] \;=\; 1.67 \cdot tm_{nav}\,[sec]$$

The drive mode "wp_follow_partial" is also accessed if the Cool Robot reaches the last waypoint within a certain distance. Then the robot is slowed down and the time between two navigation cycles is short to allow the robot to get very close to the waypoint. If navigating with full speed, the distance between two navigation cycles is greater than 30 m. That makes it hard or impossible to reach a certain point within a range of 10 m. So the robot changes to partial speed once within a range of 100 m of the last active waypoint in the list. The time between two navigation cycles is set in "tm_nav_wp" and set to 10 seconds.

4.4.3 Manual Operator

The drive mode "manual_operator" gives the user the ability to control the robot manually with the keypad of a laptop or computer with radio connection within a range of 1.2 km (0.78 miles). Is implemented to be able to drive the robot out of a garage for testing or any other purposes. The functions for the manual control are written in the drive.lib. They split the range of negative full speed to positive full speed into 20 steps. Every hit on the keypad is equal to a 10% change of the motor speeds. The robot is accessed with the five keys w, a, s ,d, q.

w: All four motor speeds are increased by the value of "motor_speed_increment" which is 10% in default as long as none of the four already is at full positive speed. If the robot is driving backwards, an increase of the nagative value will force it to go slower backwards. If the commands are sent through the radio connection, more then one key can be sent at one time. A string of ten times "w" should be avoided, since the stress on the motor, the gearhead,

the support tubes and the axes is very high then because there is almost no delay between the commands.

s All four motor speeds are decreased by the value of "motor_speed_increment" as long as none of the motor speeds already is at full negative speed. If driving forward, the robot is decelerated 10%.

a By sending the key "a" the motor speed A and motor speed B are decreased $\frac{angle}{2}$ and motor speed C and motor speed D are increased $\frac{angle}{2}$. The variable "angle" defines the radius for a turn , if "a" was sent once. As the robot is skid steered, it can turn on one place by driving one side of the wheels at 100% positive speed and the other at 100% negative speed.

If the robot is driving forward it will make a left turn with the key "a" but if the robot is driving backwards it will make a right turn as the direction of "front" changes.

d The command "d" makes a right turn instead of a left turn if driving forwards and a left turn instead of a right turn if driving backwards.

q The command "q" forces the robot to stop within a maximum time of two seconds. It decreases all four motor speeds by 10% in a time delay of 200 milli seconds. That means if driving with full speed, it takes 2 seconds to come to a full stop but only 1.167 seconds for a full stop if driving at partial speed for example. This function is also used to stop the robot if detecting a high tilt angle in drvie mode "wp_follow_full".

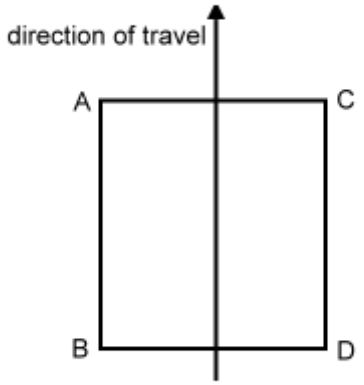


Figure 4.7: *Overview of motor placement*

4.5 Perspective on further drive modes

Our task was to have an autonomous driving robot following waypoints. But as the Cool Robot is driving along for weeks, many interrupts can happen. A blizzard can force the robot to turn into the wind, or force it to stay at one point to recharge the batteries. The following drive modes need to be implemented in the system in the future.

4.5.1 Charge cycle

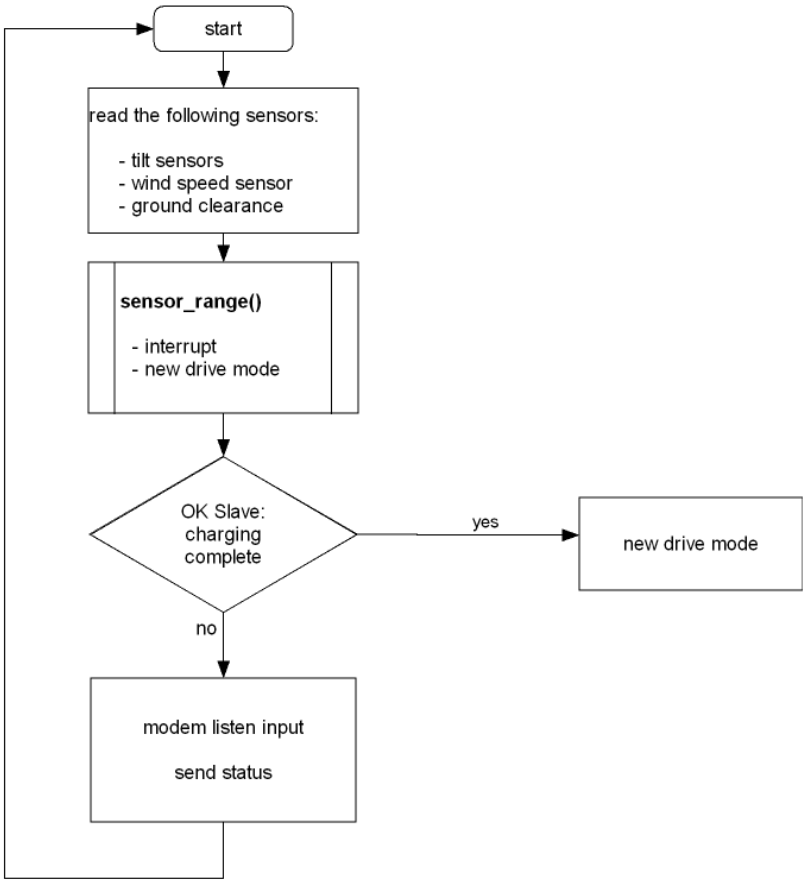


Figure 4.8: *Drive mode charge cycle*

The drive mode "charge_cycle" will be necessary. The robot is powered with solar energy which is not available all the time. During the austral summer in Antarctica we have almost 18 hours of sunshine, but blizzards are possible. And if the energy does not allow a movement

at all, the energy consumption has to be reduced to a minimum to recharge the batteries with the available sun power. The robot should be still able to read the sensors such as wind speed to turn into the direction of the wind and should still have a connection to the user for a status request for example. A possible configuration could be the routine in Figure 4.8.

4.5.2 Stationary data aquisition

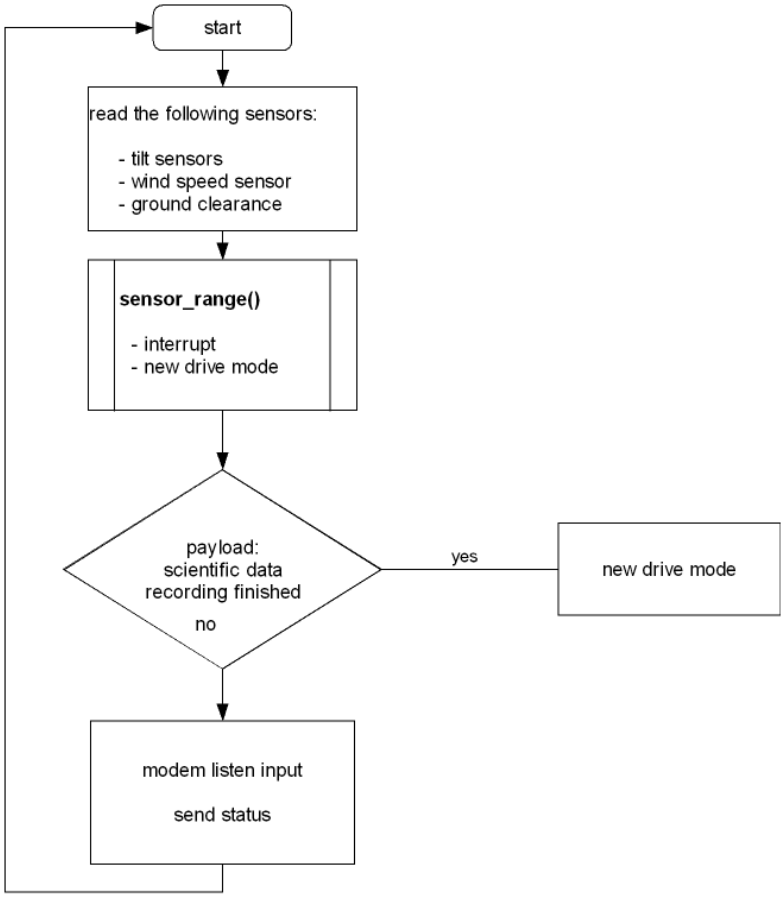


Figure 4.9: *Drive mode stationary get data*

The parameters for the scientific payload have not been specified yet. But as measurements have to be taken stationary, the robot changes into a drive mode, which is similar to "charge_ cycle", except that some energy is used for the payload and that most of the bandwidth is reserved for transmitting scientific data. A possible routine is pointed out in Figure 4.9.

4.5.3 High centered

This drive mode is possibly the hardest to predict. The idea behind it is to get the robot back to navigating again once it is high centered on a large feature with two or more wheels with not contact to the snow. The Cool Robot has a ground clearance of 23 cm which is not large, but it could handle all the terrain during the tests on mascoma lake. Sastrugi features have one sharp edge with slopes of not larger than 40°. If the other side rises slowly, that is only a problem if the robot drives parallel to that edge with one side of the wheel at the lower end and one side driving on top of the sastrugi. If the feature rises rapidly, the robot will simply drive against it like it is an obstacle and will not make any movements although the wheels are turning. The currents will not drop and the motor velocities will not go up. The way to detect that will be a task for the next students.

To detect a high centered position is already implemented in one of the interrupts. The robot is stuck in a high centered position, if it is centered on a high feature with the bottom of the chassis and two or more wheels with no contact to the snow. It is not able to drive on. The sensors for motor currents, motor velocities and tilt angle detect this situation and the drive mode "high_centered" is called to get all four wheels back on the snow. This has to happen by designing a method to turn each wheel in a different direction and use the weight of the wheels to force the robot to slide to one side and be able to drive back off that feature.

At the moment I have written a routine that tries to drive the robot backwards off that obstacle and tries to turn one side of the wheel forwards full speed and the other side backwards.

Chapter 5

Communication of CoolRobot

According to the overall concept of the Cool Robot it should basically be able to travel autonomously along a predefined track on the Antarctic plateau. The track will be defined through an arbitrary number of waypoints that consist of GPS coordinates. Those can be implemented in the control algorithm of the robot before it starts its journey.

So why communication between robot and base? There are a number of different reasons for a communication system. The first and most important is the ability to alter the course of the robot once it is started. At some point it might be essential to have the opportunity to stop the mission and make the robot return to its base immediately. In other cases one may want to add points to the route to take extra measurements, or just alter existing waypoints anticipating possible problems on the planned route. Another argument is the fact that the robot might get into some critical situation. Although the terrain on the arctic plateau is supposed to be quite even it is possible to get stuck on one of the Sastrugi features. Some testing on hard snow with features like those on the Antarctic Plateau showed that there is a possibility to get stuck if the robot runs longitudinal onto one of those features. In that case the robot must be able to realize it is stuck, which is part of the navigation process, try to get itself unstuck and if this is not possible it has to send a status report back to the base. This report must contain at least the position at which the robot got stuck to be able to pick it up. It might also be useful to have all other available sensor data to get an exact idea of the situation. With enough information about the actual situation of the robot it might be possible to free it by driving manually or

with a special set of commands to move it based on the momentum of the wheels.

There are lots of other possible errors imaginable that could force the robot to stop. For example, problems with the power system, low batteries, burned fuses or other hardware or software-related problems. Finally it might be necessary to know where the robot is and in what condition. It is quiet possible that the robot is not going as fast as is supposed to and therefore is not able to finish the planned route within the time alloted for its mission. So, it is important to check the progress periodically and be able to alter the track or cover extra distance if it is ahead of schedule. Depending on the kind of scientific application of the Cool Robot, it might also be necessary to send some of the measured data to base.

5.1 IRIDIUM Communication

Within the concept development of the robot the decision was made that an IRIDIUM modem shall be use for the data-communication in the Antarctic. Iridium is a global satellite based cell phone technology. At the moment, IRIDIUM is the only provider of satellite voice and data solutions with coverage of nearly the whole surface of the earth including all oceans, airways and also the arctic and Antarctic region. Due to the long distances of several hundred kilometers the robot is covering IRIDIUM is the only way to stay in touch with Cool Robot. Since Cool Robot is a lightweight construction there is no possibility to use big, heavy radios with the range needed in this application. Another argument for not using such a radio is the power consumption and power output, since this may affect the electronics controlling the robot and also the measurements of the carried payload. The big advantage of IRIDIUM technology is its global availability and the fact that it makes no difference if the operator is also in the Antarctic or somewhere else in the world. The disadvantage is the high price and slow bandwidth of 2400Bit/s. According to this, there will be no permanent connection but rather only data-transfer when needed. Therefore, either the robot or the operator will have to establish the connection. Figure 5.1 provides an example IRIDIUM application.

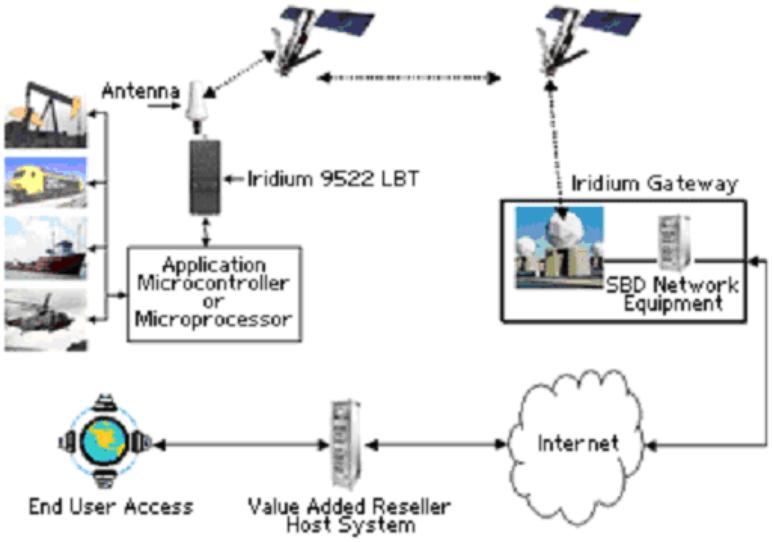


Figure 5.1: *Example for an IRIDIUM modem application*

The IRIDIUM System was developed by Motorola in 1980 as a personal communication system for users that need communications access to and from remote areas where no other form of communication is available. It consists of 66 operational low altitude satellites grouped into six polar planes of 11 satellites. Each of the satellites performs as node of the telephony network. 13 additional satellites act as backup system. The satellites circle the earth once every 100 minutes in a near polar orbit at an altitude of 780km. On the surface the system comprises system control segment and telephony gateways connected to the telephone system on earth. The uplink to the satellites uses TDMA and FDMA multiplexing methods. TDMA reads Time Division Multiple Access which is a technology for delivering digital wireless service using time-division multiplexing (TDM). The radio frequency is divided into time slots which are then allocated to multiple calls, so a single frequency is able to carry multiple, simultaneous data channels. FDMA on the other hand means Frequency Division Multiple Access.

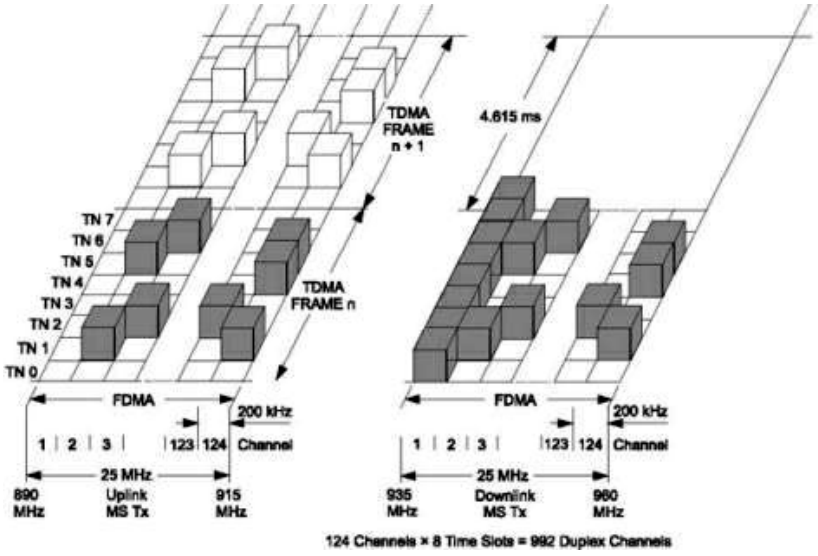


Figure 5.2: *FDMA versus TDMA*

In case of IRIDIUM the frequency band is 1616-1626.5MHz and is divided into 20 channels and each of those channels is time divided into 4 TDMA channels. This multiplies to 80 channels per cell. Considering that each of the 66 satellites has 48 cells this makes up a total of 3168 cells. Only 2150 cells are active at a time, multiplied by 80 channels per cell the system allows up to 172000 calls simultaneous. The bandwidth for each of the channels is 2400Bit/s when transmitting data and 4800Bit/s on a voice call.

5.1.1 The A3LA-I IRIDIUM modem

The IRIDIUM-modem or IRIDIUM Subscriber Unit (ISU) used when Cool Robot will be deployed in the Antarctic is a Motorola 9505 A3LA-I. The unit will not be purchased but rather borrowed for Cool Robots mission in the Antarctic. Thus, no example is available for testing at the moment. I was only able to familiarize myself with some facts as well as the handling and operation of this equipment.

Figure 5.3: *Motorola 9505 A3LA-I IRIDIUM modem*

Other than normal IRIDIUM mobile phones this modem is special designed for the use with computer or micro controller based applications. Using the modem alone no IRIDIUM call can be completed because some additional equipment is needed. An antenna is required, since the modem doesn't come with one. Lots of different antennas for almost every requirements are available on the market. The one preferred for our project is the NAL Research SAF2040 family of mobile flat mount antennas. They are designed to withstand harsh environmental influences, are very small in dimension and most important the frequency range is fitted to the the IRIDIUM requirements, which means they provide continuous coverage from 1610 - 1626.5MHz. The various Types of antennas of this family only differ slightly in their dimensions and electrical specifications.

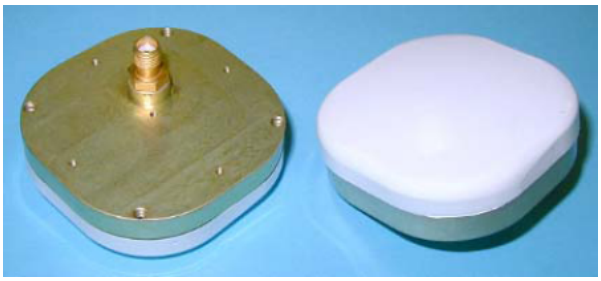


Figure 5.4: *SAF2040-E mobile flat mount antenna*

Due to the fact that there is no input or control device included with the A3LA it must be attached to a micro controller or computer equipped with an RS232 serial port. All commu-

nication between the ISU and the Data Terminal Equipment (DTE i.e. micro controller) takes place over this serial connection. Depending on the attached DTE two wiring possibilities are given. First a full 9-wire interface, incorporating hardware handshaking and flow control or a 3-wire interface where only ground GND, receive RX and transmit TX are connected. Connecting the A3LA to the Jackrabbit micro controller a 3 wire interface will be sufficient, since hardware handshaking and flow control are not essential for us and would complicate the communication routines and especially the wiring of serial port E. Since for this kind of serial communication no SPI protocol is used it can take place while all other systems of Cool Robot are running. The only disadvantage of the 3 wire interface is that some settings (see chapter 5.1.1.2) must be accommodated to this circumstances. When connecting the A3LA to a personal computer the 9-wire interface is probably the better solution.

5.1.1.1 Using the A3LA-I IRIDIUM modem

For the control of the A3LA the the industry standardized basic (Hayes) AT command set plus a extended AT command set is used. AT means Attention Code and signals the modem that one or more commands are to follow. Both types of commands have different syntax to query and adjust their settings. As these commands are industry standard language to communicate with a modem it is used with most modems available on the market. All commands in this language must begin with the characters "AT". The only exceptions are the repeat command "A/" and the escape sequence "+++". Many of the basic commands consist of one single alpha character in other cases a special character (like %, $ or *) precedes the alpha character. Most of the extended commands use a "+" prefix plus alpha characters. For example:

Extended Cellular Commands
+C prefix - Used for GSM cellular phone-like functions (Standards: ETSI specifications GSM 07.07)

Extended Data Compression Commands
+D prefix - Used for data compression (Standard: V.25ter)

Extended Generic Commands

+G prefix - Used for generic DCE issues such as identities and capabilities (Standard: V.25ter)

Extended Interface Control Commands

+I prefix - Used to control the DTE interface (Standard: V.25ter)

Motorola Satellite Product Proprietary Commands

-MS prefix - Proprietary to the Motorola Satellite Series product line

Both, the command prefix ("AT") as well as the command sequence itself can be typed in upper or lower case but must not be a mix of both. Furthermore many commands can be typed within one command line divided by spaces for better reading if desired. Figures 5.5 and 5.6 show example commands and command lines.

`ATX0`	(set basic command `ATXn` to `n=0`)
`AT&V`	(execute basic command `AT&V`)
`AT+GSN`	(execute extended command `AT+GSN`)
`AT+CBC=?`	(query the valid range of responses of extended command `AT+CBC`)
`AT+CPBR=1,12`	(execute extended command `AT+CPBR` with parameters `1` and `12`)
`AT-MSVLS?`	(query the current setting of extended command `AT-MSVLS`)

Figure 5.5: *Some sample commands with explanation (AT manual for A3LA)*

`at x 0 &v +gsn +cbc=? +cpbr=1,12 -msvls?`	(all lower case)
`AT X 0 &V +GSN +CBC=? +CPBR=1,12 -MSVLS?`	(all upper case)
`ATX 0 &V +GSN +CBC=? +CPBR=1,12 -MSVLS?`	(space omitted between `AT` and `X`)
`ATX0 &V +GSN +CBC=? +CPBR=1,12 -MSVLS?`	(space omitted between `ATX` and `0`)
`ATX &V +GSN +CBC=? +CPBR=1,12 -MSVLS?`	(`0` omitted from `ATX0`)
`ATX;&V;+GSN;+CBC=?;+CPBR=1,12;-MSVLS?`	(semicolon separators)
`ATX&V+GSN+CBC=?+CPBR=1,12-MSVLS?`	(no separators)

Figure 5.6: *Example for different ways to type commands (AT manual for A3LA)*

The only limit hereby is the size of the command line buffer which normally accepts 39 characters including the "AT" prefix. Spaces, carriage return <CR> and line feed <LF> do not go into the buffer and therefore don’t count against the 39 character limit. In case of a syntax error within the command line or if the 39 character limit is exceeded the whole command line

will be ignored and an ERROR result code will be returned. Possible result codes are shown in Table 5.11.

5.1.1.2 Outline on AT commands

In this section some of the most common commands of the AT command set will be introduced. Essential commands will be explained by some examples including result codes as answers from the modem. With this short introduction the reader should be able to originate a data call , switch between in-call data mode and command mode, end a call and adjust some basic settings that might be important for use within the CoolRobot project.

"+++"
So called escape sequence switches from in-call data mode to in-call command mode. The modems answer is "OK".

"A"
The answer command "A" forces the modem to answer an incoming call immediately.

"A/"
Repeats the last command issued to the modem unless it was reset or power was interrupted. "A/" is not followed by a <CR>. The answer depends on the last command.

"AT"
As mentioned earlier "AT" is the prefix for all commands except the repeat instruction "A/" and the escape sequence "+++". "AT" entered on its own forces the modem to answer "OK".

"Dn"
Is used to dial a data or voice call number. Syntax is ATDnx...x, where n is a modifier for the dial instruction and x...x represents the number to dial. Allowed values for x are 1234567890*#ABC. The modifier alters the way the A3LA is dialing:

L	redial last number
P	use Puls dialing
T	use Tone dialing (it doesn't matter whether Puls or Tone dialing is used)
+	international dial prefix
;	start a voice call (without this a data call is originated)
>	used to dial a number from the phone book

Table 5.1: *Modifiers for Dn.*

"En"

Determines whether characters are echoed locally. Echoing characters locally should be disabled on the CoolRobots modem (see chapter 5.2.1.2 for explanation).

n = 0	characters are not echoed to the data terminal
n = 1	characters are echoed to the DTE.

Table 5.2: *Modifiers for En.*

"Hn"

Used to hangup a data or voice call originated with ATD, ATA/ or ATS0=n answer commands. A zero value for n places the modem on the hook.

"On"

The online command switches from in-call command mode to in-call data mode. Any value n=0 to n=255 is allowed but does not change the effect of the command.

"S0=n"

Sets the modems S0 register, which holds the setting for auto-answering to the value n carries. Every value higher than 0 enables the auto-answering function. n=0 disables auto-answering. It should be a good idea to enable this setting on the CoolRobots A3LA since answering a call manually requires an extra function or routine that can be omitted using this setting.

"Vn"

This sets the response format the modem uses either numerical or textual. n=0 causes numerical responses whereas n=1 causes textual answers. For the use with a PC the textual (Verbose) mode might be the better way, whereas for the use with the Jackrabbit numerical answers might be easier to process.

"Zn"

The "Zn" command acts as a soft reset and restores one of the two available user defined configurations. See description of "&Wn" for information on storing user defined configurations.

n = 0	restore user settings profile0.
n = 1	restore user settings profile1.

Table 5.3: *Modifiers for Zn.*

"&Cn"

This setting changes the behavior of the modem to the Data Carrier Detect signal (DCD), which indicates whether the modem is connected to a remote station for data exchange or not.

n = 0	DCD is forced on all the times.
n = 1	DCD indicates the connection status.

Table 5.4: *Modifiers for &Cn.*

"&Dn"

This option is used to determine the A3LAs behavior on the Data Terminal Ready (DTR) signal. This signal can be used to end a call. The value of n determines the reaction of the modem to a transition of DTR from ON to OFF during a call. Valid values for n are:

n = 0	DTR is ignored
n = 1	the modem changes to in call command mode and if DTR is not restored ON within 10 seconds the call is terminated.
n = 2	the modem changes to on-hook command mode (call is terminated)
n = 3	the modem changes to on-hook command mode and AT command profile 0 is reset

Table 5.5: *Modifiers for &Dn.*

"&Kn"

This setting selects which flow control method is uses for the communication between DTE and modem.

n = 0	no flow control is used (flow control is disabled)
n = 3	enables RTS/CTS (Ready To Send/Clear To Send) hardware flow control
n = 4	enables XON/XOFF software flow control (a standard flow controll method to prevent overflow/overrun)
n = 5	enables both, RTS/CTS and XON/XOFF flow control

Table 5.6: *Modifiers for &Kn.*

"&Wn"

This command can be used to store the active settings in one of two available profiles.

n = 0	stores the active configuration as profile0 and
n = 1	stores the active configuration as profile1.

Table 5.7: *Modifiers for &Wn.*

+CBST

Select the bearer service type for mobile originated calls. This setting determines which modulation protocol is used for the data transmission during a data call. The command must be in this form AT+CBST=<speed>,<name>,<ce>.

<speed>	can have the following values:
0	Autobauding
1	300 bps V.21
2	1200 bps V.22
4	2400 bps V.22bis
6	4800 bps V.32
7	9600 bps V.32 (default)
65	300 bps V.110
66	1200 bps V.110
68	2400 bps V.110
70	4800 bps V.110
71	9600 bps V.110
<name>	takes the following value:
0	data circuit asynchronous
<ce>	can only take the following value:
1	non-transparent

Table 5.8: *Possible values for +CBST command.*

As mentioned earlier some settings must be adjusted if a 3-wire interface is used to connect the A3LA with the DTE. When operating with a 3-wire connection, the following limitations apply:

AT&Dn must be set to AT&D0 to ignore the DTR input from the data terminal, as it will not be present as an input from the micro controller.
AT&Kn must be set to AT&K0 for no flow control or AT&K4 for XON/XOFF software flow control, as RTS (Request To Send) and CTS (Clear To Send) hardware flow control signals will not be present.
AT&Cn setting will have no affect, as DCD (Data Carrier Detect) output to the data terminal will not be present.
AT&Sn setting will have no affect, as DSR (Data Set Ready) output to the DTE will not be present.
RI (Ring Indicate) output to the DTE will not be present.

The following will describe an example for a communication between the A3LA IRIDIUM modem and a personal computer. In this case data call is established, data will be transmitted and the call is terminated by side that started the call.

`AT+CBST=4,0,1`	asynchronous communication at 2400Bit/s it is sufficient to set this once and maybe save the profile using the "Wn" command
`OK`	acknowledgment from modem
`ATD+1603123456`	dial international (American) number 603-123-456
`CONNECT 9600`	answer from modem: connection to remote host is established baudrate between DTE and modem is 9600Bit/s
<—>	now the data transfer takes place, every data passed to the modem will be sent to the remote modem
`+++`	escape sequence forces the modem to in-call command mode
`OK`	acknowledgment
`ATH0`	places modem on the hook (terminates call)
`OK`	acknowledgment

Table 5.9: *Example: originating a data call.*

The next example is quiet similar to the one above, only this time the data call is not originated from the considered modem but from a remote station.

`RING`	indicates an incoming call
`ATA`	manually answer the call (not applicable if ATS0=1 is set)
`CONNECT 9600`	answer from modem: connection to remote host is established baudrate between DTE and modem is 9600Bit/s
<—>	now the data transfer takes place, every data passed to the modem will be sent to the remote modem
`NO CARRIER`	the call has been terminated by the other side the modem switches back to on-hook command mode.

Table 5.10: *Example: incoming data call.*

These two examples show the most of the basics needed for the use of the A3LA IRIDIUM modem related to the CoolRobot project. All other shown commands are only needed to adjust settings depending on the application the modem is used for either connected to a PC or to the Jackrabbit micro controller. Table 5.11 gives a review of the essential return and error codes the IRIDIUM modem may produce.

Numeric	Textual	Description
0	'OK'	Acknowledges execution of command; voice call connection has been established.
1	'CONNECT'	Data call connection has been established.
2	'RING'	Incoming data or voice call received (unsolicited).
3	'NO CARRIER'	Data or voice call connection terminated.
4	'ERROR'	Command not accepted.
5	'CONNECT 1200'	Data call connection established at 1200 bps.
6	'NO DIALTONE'	No dial tone detected.
7	'BUSY'	Busy signal detected.
8	'NO ANSWER'	Data or voice call connection completion timeout.
9	'CONNECT 0600'	Data call connection established at 600 bps.
10	'CONNECT 2400'	Data call connection established at 2400 bps.
11	'CONNECT 4800'	Data call connection established at 4800 bps.
12	'CONNECT 9600'	Data call connection established at 9600 bps.
44	'CARRIER 1200/75 '	Data rate detected at V.23 backward channel.
48	'CARRIER 4800'	Data rate detected at 4800 bps.
49	'CARRIER 7200'	Data rate detected at 7200 bps.
50	'CARRIER 9600'	Data rate detected at 9600 bps.
67	'COMPRESSION: V.42 bis'	Data call connected with V.42bis compression enabled.
69	'COMPRESSION: NONE'	Data call connected with no data compression.
as textual	'+DR: V42B NONE'	Data call connected with no data compression.
as textual	'+DR: V42B TD'	Data call connected with V.42bis compression enabled on transmit direction.
as textual	'+DR: V42B RD'	Data call connected with V.42bis compression enabled on receive direction.
as textual	'+DR: V42B'	Data call connected with V.42bis compression enabled on both transmit and receive direction.

Table 5.11: *Overview of AT command result codes.*

5.1.2 Prospect on further use

In contrast to the communication via the radio modem (see chapter 8.4) where a more or less permanent connection is established before Cool Robot starts a journey, here only short time frames are available to exchange data between the robot and an operator or supervising base station. For each of those time frames a dial up connection must be started either from the robot or the remote station. There should be no problems with an incoming call to the robot, since the IRIDIUM modem will be in standby all the time. As soon as a call arrives the modem will send a "RING" signal to the micro controller indicating an incoming call. The micro controller will accept the call and receive and compute the incoming data.

The other way around it is very similar: the micro controller passes the command to dial the number of the base station and transmit its data as soon as the connection is established. The only issue will be to determine when the robot will create a connection and why. Certainly the base needs to know whenever Cool Robot encounters problems on its way or stops for some reason. There may also be a need for event-driven status reports the robot should give in repetitive intervals. I wrote some basic code for an IRIDIUM-based communication including some functions to originate and end a call, accept an incoming call as well as an adapted main routine "mainprog_2.3x. But all this is only a rough frame that must be fitted to the needs of the Cool Robots mission once all general conditions are clear and the IRIDIUM equipment is available for testing.

5.2 Radio Communication

Due to high cost of the Iridium-connection another communication is needed for the testing during the development of the robot. During this time a more or less permanent connection is required and a range of several hundred meters is sufficient. The cheapest and easiest solution for a short-range digital wireless communication is a packet radio connection. A packet radio station consists of three basic parts as shown in Figure 5.7.

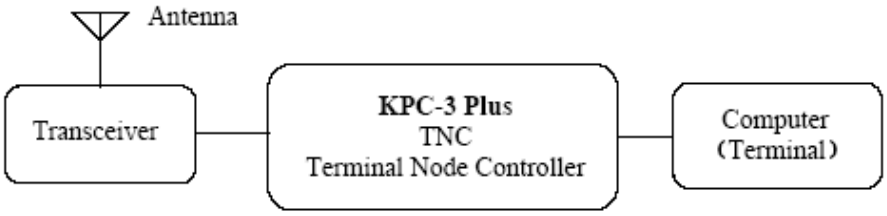


Figure 5.7: *Components needed for packet radio communication*

- The transceiver with antenna:
  (1) sends and receives radio signals to and from your antenna and
  (2) passes audio signals back and forth between itself and the TNC.

- The TNC (Terminal Node Controller):
  (1) translates audio signals into digital information and vice versa,
  (2) performs a number of control and information storage functions, and
  (3) communicates digitally with your computer.

- The computer communicates digitally with the TNC, so you can:
  (1) view messages received from the transceiver or stored in a mailbox (i.e., PBBS),
  (2) use the computer to send data to, and receive data from, other stations, via the TNC and your transceiver, and
  (3) control the operation of the TNC.

In our case the transceivers were a set of two Cobra FRS 105 hand held radios, which were replaced with ICOM 4088 radios. As Terminal Node Controllers two Kantronics KPC3plus packet radio modems are used and as Terminals the Jackrabbit RCM3100 micro controller is used on the robot-side and a personal computer with terminal software such as "Hyper-Terminal" can be used on the user side. Those components are fairly cheap and permanent connection can be established without any extra expense.

5.2.1 The Kantronics KPC3plus packet radio modem

The packet radio modem we are using is a commercial Kantronics unit priced $186 (figure 5.8. It is fairly lightweight weighing only 320g and small, measuring 133x133x21mm. Another positive aspect is the low current just below 30mA at 6-25VDC when the unit is active and the control LEDs are on. This power consumption can be cut down to around 15mA at 6-25VDC by turning off the control LEDs using the command "LEDS OFF". The modem connected to the PC is powered by a 9V battery and the other modem inside the CoolRobot is supplied by 10VCD from the internal housekeeping power supply.

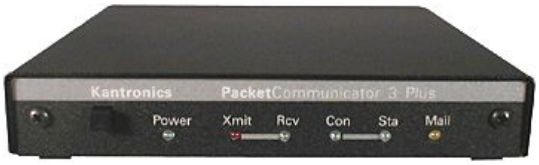


Figure 5.8: *KPC3plus front view*

As Modem is a short form of Modulator/Demodulator this device transforms the digital input signal it receives via an RS232 serial interface into an analog signal a common FM transceiver can handle. The KPC3plus uses the CCITT (Comité Consultatif International Téléphonique et Télégraphique) V.23 standard. This standard determines parameters for a 1200Bit/s 1300/2100Hz FSK full duplex communication. The data is transferred between two stations with a baud rate of 1200Bit/s in both directions. Data can be transferred both directions simultaneously, but in this standard only one direction can use the 1200Bit/s and in the reverse direction the baud rate is just 75Bit/s. The sense in this is that a package of data is sent from one modem to the other using the fast baud rate the receiving modem is able to respond with a short acknowledgment or request to resend at 75Bit/s while receiving more data at 1200Bit/s. No matter which station is sending, the data package is always transferred using the fast baud rate, only the response uses the slower speed. The digital data is encoded using FSK (Frequency Shift Keying). The digital information must be transformed into something a commercial radio can transmit; therefore the logical values "0" and "1" are represented by two different frequencies within the hearable range. A space or "0" is presented by 2100Hz and "1" (mark) by 1300Hz. This speech-like formation can be transmitted by virtually every radio.

Figure 5.9 shows the principle of frequency shift keying. The first diagram shows 1300Hz and 2100Hz sine waves and diagram two a digital signal of altering "0" and "1". The last diagram shows the corresponding analog signal.

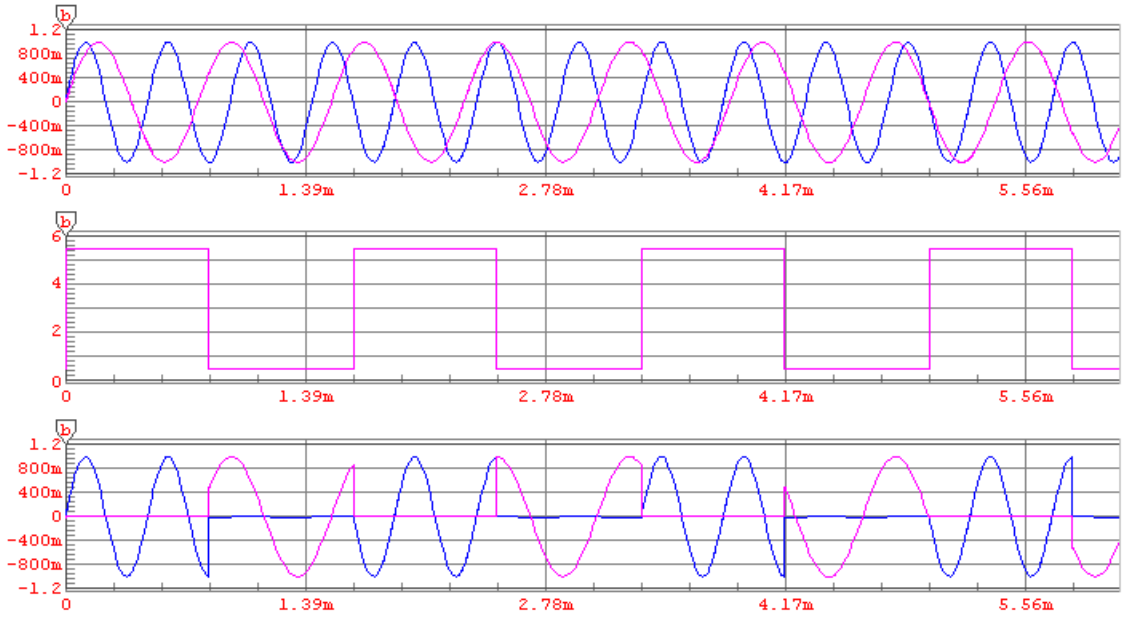


Figure 5.9: *1300/2100Hz Frequency Shift Keying*

5.2.1.1 Setting up the KPC3plus

This part describes how to set up the KPC3plus including basic wiring when connecting it to a computer or the Jackrabbit micro controller as well as connecting it to a transceiver. Figure 5.10 provides a basic wiring overview. For further information the KPC3plus manual is recommended.

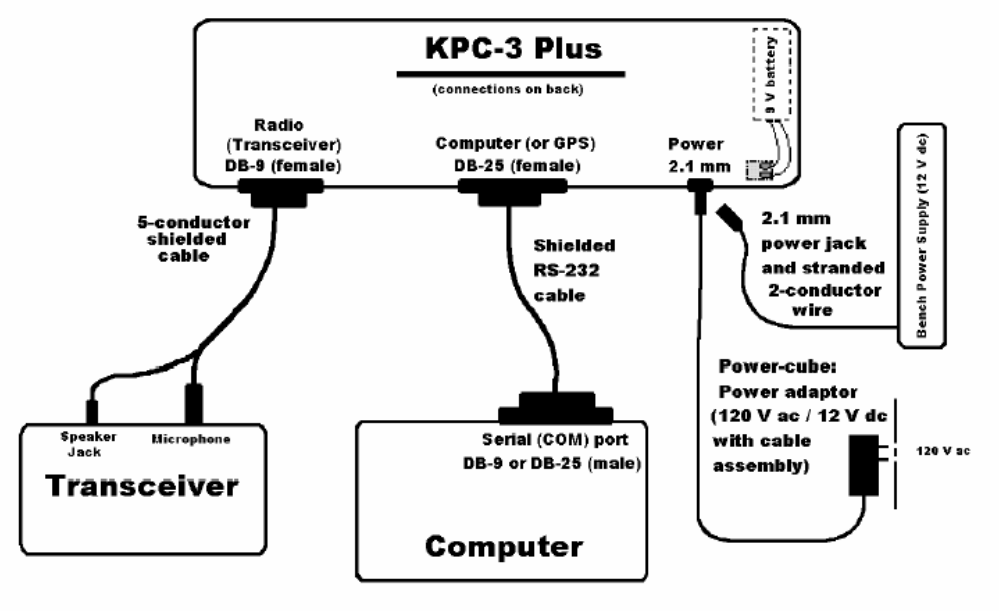


Figure 5.10: *Basic wiring of the KPC3plus radio modem*

To connect to the radio modem a computer with a RS232 interface and a terminal-software like Hilgreaves HyperTerminal, which is included in most MS Windows installations, is required. To connect the KPC3plus to a PC an ordinary serial cable with a male and a female DB-9 connector in combination with the included DB-9 to DB-25 adapter. The modem uses an 25 pin serial connector, so either the adapter must be used or a custom cable can be built with the following wiring:

KPC3plus	Computer
(DB 25)	(DB 9)
2	3 TXD
3	2 RXD
4	7 RTS
5	8 CTS
7	5 SG
6	6 DSR
8	1 DCD
20	4 DTR

Table 5.12: *Pinouts RS232.*

The connection to the micro controller is little more complicated. For the communication with the modem serial port E is destined. The Jackrabbit has 6 serial interfaces but only two of them, serial port B and C, are immediately usable from the evaluation board. Serial port A is used for programming and debugging using the DynamicC software and ports D, E and F are available, but only directly from the micro controller. The problem here is the micro controller's logic uses 3.3V whereas a RS232 interface uses 5V logic. Furthermore the Jackrabbit's serial ports construe 3.3V (high) as logical "1" and 0V (low) as logical "0". RS232 is the other way around, low 0V are interpreted as "0" and high 5V as "1".

Therefore a RS232 driver needed to be installed on the evaluation board. The driver of our choice is a -40°C rated Maxim MAX3232I RS232 line driver/receiver. This 16 pin surface mount IC is good for two serial interfaces, in our case serial port E and F. For the communication between micro controller and radio modem or rather the IRIDIUM modem later on serial port E is reserved and port F will be used to interface with the data logger.

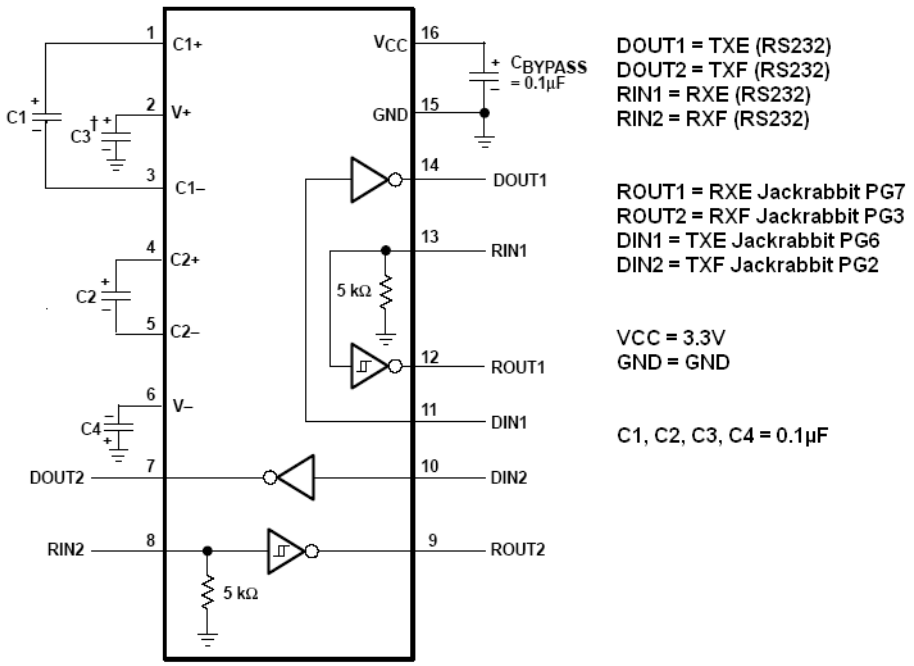


Figure 5.11: *Pinouts MAX3232 RS232 line driver/receiver*

The RS232 driver/receiver is soldered to a small multipurpose board including all necessary capacitors, this work was done by Alex Streeter. The small board is located on the empty area

on the RCM3100 evaluation board. The two serial interfaces are conducted on a 10 pin IDC connector for ribbon cable.

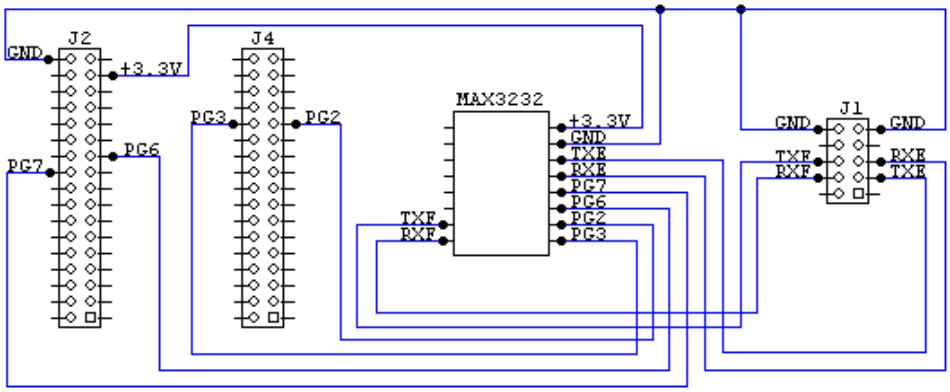


Figure 5.12: *Wiring of the MAX3232 on the RCM3100 evaluation board*

Another issue is the connection between the KPC3plus and our transceivers. One can find a lot of wiring examples within the KPC3plus manual, but none for Cobra radios. So in the first place we tried to figure out a way ourselves by soldering the wires for PTT (Push To Talk), RX (Receive data), TX (Transmit data) and GND (Ground) to the circuit board of the radio. But none of the things we tried worked out. So we borrowed another set of hand held radios, two ICOM 4088 from Prof. Cooley, because for ICOM radios some wiring examples were available within the KPC3plus manual. The most reasonable of the different suggestions to do this wiring was using the microphone and speaker jacks available on top of the radios. As suggested in the KPC manual 5-wire, shielded cable was used. To keep electro-magnetic interference as low as possible only the very last centimeters of the cable are unshielded and the capacitor, as well as the resistor are placed within the housing of the microphone plug.

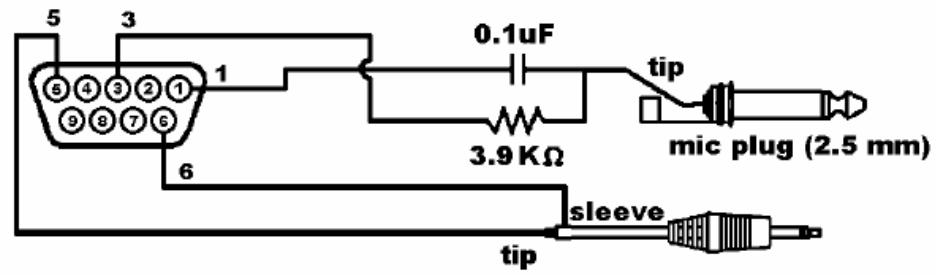


Figure 5.13: *Wiring suggestion for ICOM radios*

This setup worked quiet well and so proved that it is possible to transfer digital data using the Kantronics packet radio modems and some commercial hand held radios as transceivers.

5.2.1.2 Using the KPC3plus

If the KPC3plus is started for the first time or after a reset it is running its AUTOBAUD-routine, trying to negotiate the baud rate with the terminal it is connected to. Therefore it is sending a request to type a "*".

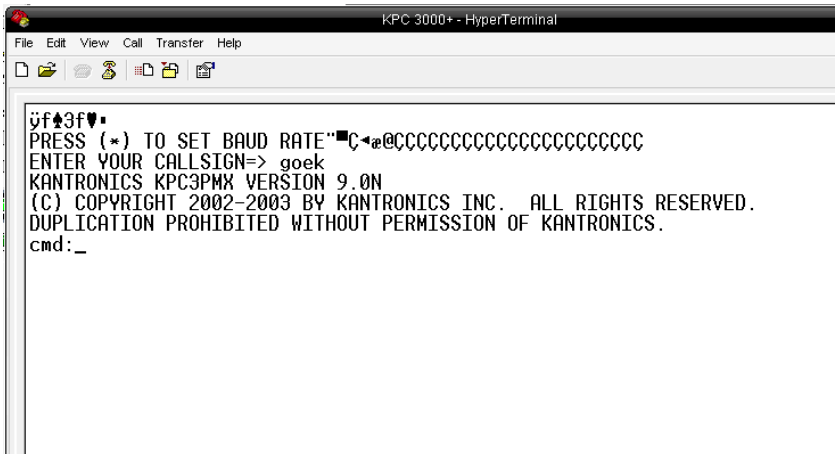


Figure 5.14: *AUTOBAUD routine running on Hyperterminal*

Once this character is typed and sent to the modem by hitting carriage return - all commands and data for the KPC3plus must be terminated by a carriage return character <CR> - the modem is able to detect the baud rate used by the terminal it is connected to. This baud rate is stored and can only be changed by erasing the modem settings memory by setting and resetting jumper J11. On the next startup of the modem it will run the AUTOBAUD routine again and the baud rate can be changed. After completing AUTOBAUD the modem asks for a callsign which will also be stored in the KPC3plus and used until it is changed. The callsigns for the two modems used are "MAHONY" for the modem on the Cool Robot and "GOEK" for the modem used with a PC. These can be changed easily typing "MYCALL <desired callsign><CR>".

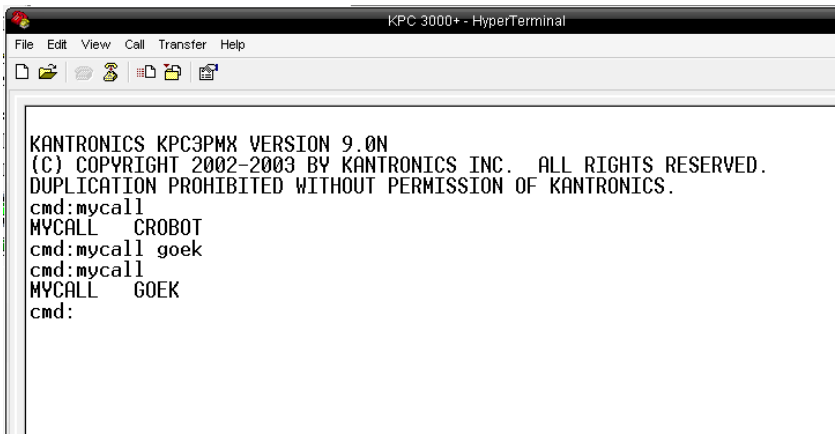


Figure 5.15: *MYCALL command using Hyperterminal*

As soon as the callsign is set the KPC3plus is ready for sending packet data. There are dozens of further settings a user can change but only one of them is off greater importance for our application. Using the "ECHO" command, one can determine whether characters sent to the modem should be echoed locally or not. For use with a personal computer and terminal software this is not very important, since this setting can also be made within the terminal software. The Jackrabbit on the other hand has no need for an echoed character. In fact this is actually bad for the communication routines, since every incoming character-string is interpreted by a function within the communication routines (see chapter 7.3.2) and may cause wrong or unwanted inputs. It would certainly be possible to compare everything received to what was send but this would waste scarce runtime and memory on the micro controller. So the Cool Robot’s modem does not echo received characters. This setting is made typing "ECHO<CR>" to check whether the option is active or not and if its on one can simply type "ECHO OFF<CR>" to turn it off. As matter of course the other way around, typing "ECHO ON<CR>" turns character-echoing on again.

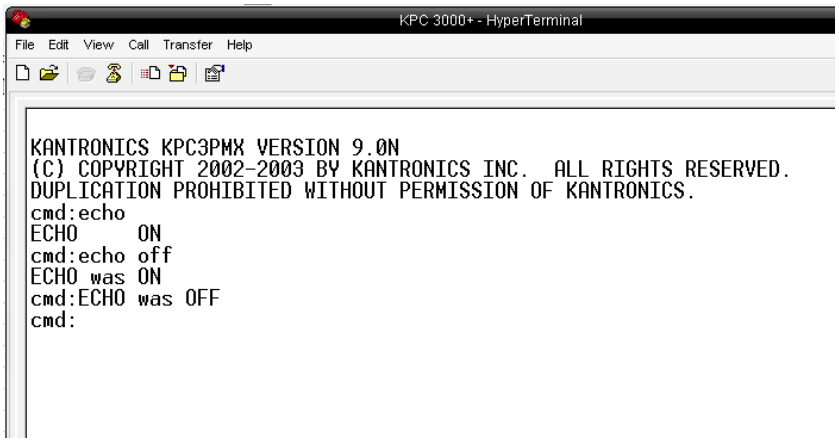


Figure 5.16: *ECHO ON/OFF command using Hyperterminal*

After connecting the radio modems to their terminals and transceivers and setting them up properly establishing a wireless connection is quiet easy. By just typing "connect <callsign> <CR>" after the "cmd:" prompt the KPC3plus tries to connect to another packet radio station with the specified callsign. The KPC is sending out a request for connection nine times approximately every 5 seconds. If it isn't receiving an acknowledgment to its request after nine attempts it determines no station with this callsign is near and prints: "retry count exceeded ***DISCONNECTED". If there is another station with the desired callsign near this station will respond to the request and determine it is connected to the host sending the request. If the requesting station receives this acknowledgment it also spots the connection and prints "***CONNECTED to <callsign>".

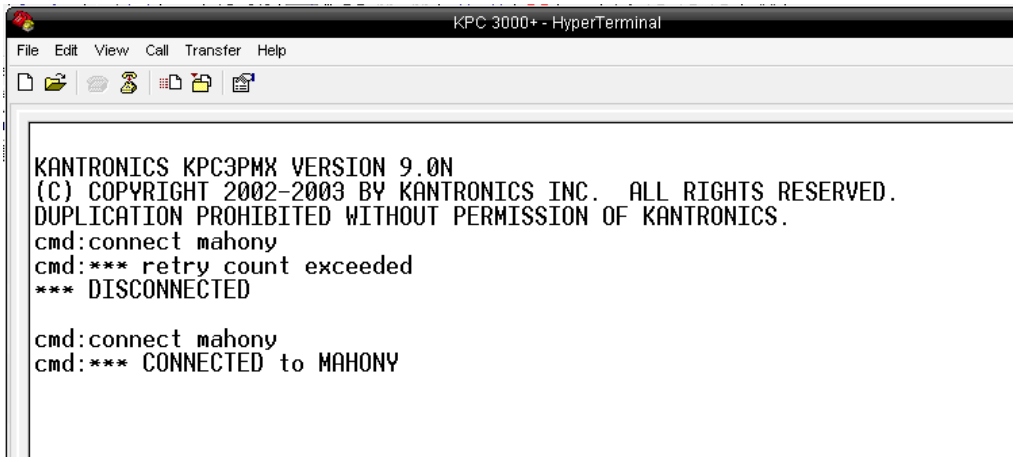


Figure 5.17: *Unsuccessful and successful attempt to connect.*

As soon as successful connection is detected the modem switches from it command mode to the data mode. The "cmd:" prompt will no longer be displayed and every typed input will be sent to the remote station if carriage return is hit. Furthermore, every incoming data will be displayed immediately. To switch back and forth between command mode and data mode pressing <Ctrl> + "c" keys at once can be used. For example to end a active connection in data mode you must switch to command mode and type "disconnect"<CR> or short "d"<CR>. The remote station will be announced of the termination of the connection and a "***DISCONNECTED" message will be displayed in the Hyperterminal window.

During an active connection all kinds of data can be passed on to the KPC3plus to be sent to the remote station. In our case almost all transmitted data consists of simple ASCII strings as commands or data input for Cool Robot. Not only short text messages but also files can be sent trough Hyperterminal by selecting "Transfer" option and "Send File...". This enables us to send longer sets of data, like a bunch of waypoints, without typing them over and over again, but store them in a ASCII text file and send them by only two mouse-clicks. The KPC3+ is able to send data-packets of a size from 1 Byte to 256 Bytes. Larger input data is divided into the needed number of 256Bytes packets. Every single packet consists of an address-header, a control part, the data itself and a checksum as shown in Figure 5.18.

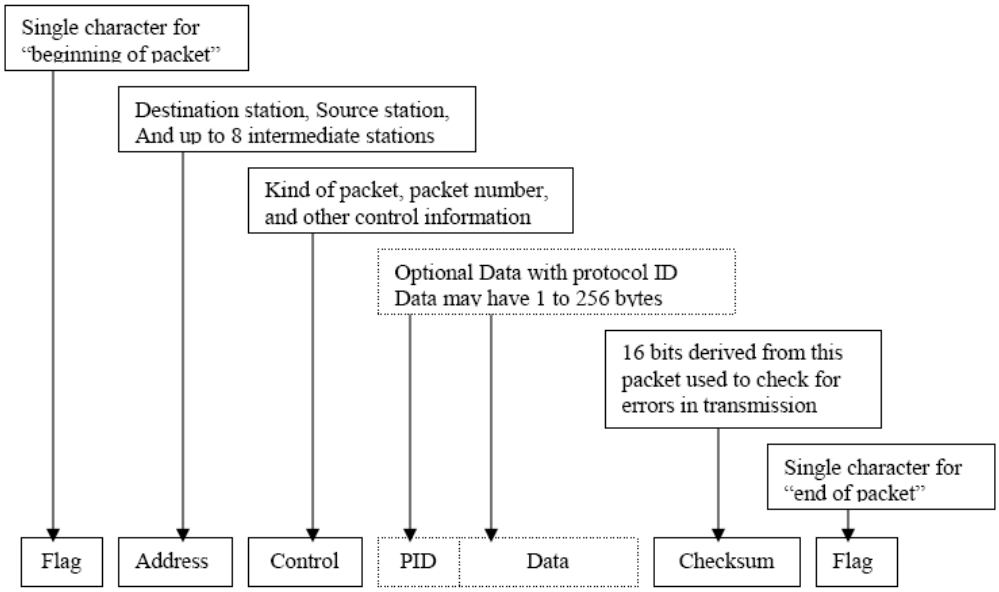


Figure 5.18: *Structure of KPC3plus data packets*

Thus, it is possible to send even big text files without any problems except the slow bandwidth of only 1200Bit/s which equals 150Byte/s. Consequential transmitting a text file of 1kByte would take approximately 6.7 seconds. Within this no extra time is included caused by the data of the packet structure and especially not the waiting time for the response from the remote station, whether the packet is received correctly or not. Which is not very fast and therefore not appropriate for transmitting bigger amounts of data. For our use this bandwidth is ok, since we got no need for transmitting data exceeding 1kByte. For example a set of 5 waypoints (see chapter 5.3.3) for the Cool Robot sum up to round about 120 Bytes plus the data caused by the structure the modem appends. Thus, the transmission of 5 waypoints will take about one second, which is absolutely sufficient for our application.

The receiving station verifies the checksum appended to the data packet and responds to the station which sent the packet whether it received the packet correctly or not. If the packet wasn’t received correct or there is no answer at all after approximately 3 seconds the packet will be sent again. After 20 unsuccessful attempts to send a packet the modem determines the connection as lost and prints a "***DISCONNECTED" message to the attached computer. If this happens either the remote station is out of range or it isn’t broadcasting any longer.

This is basically what is needed to use the KPC3plus radio modem to controll Cool Robot remotely either for driving it manually, get information on the robots condition or send new commands or waypoints.

5.3 Controling the CoolRobot via radio link

One major goal of my work was the ability to control Cool Robot remotely. This includes remote manual driving of the robot as well as getting information about the robots status without having a personal computer attached to it by wire. This feature is quite important for serious testing with the robot, since it is important to know what is going on with the control and navigation algorithm of the robot. Obviously it is very inefficient and also inconvenient walking next to the robot holding a laptop and observe the robots behavior,especially in fairly cold and windy weather conditions. The idea is to be able to observe and controll the robot

from a car waiting in some distance or maybe follow the robot within a certain range. Within this section the reader will be introduced to the operation of Cool Robot via the radio link. I am going to explain how a connection between robot and operator can be established and terminated, how different types of data can be transmitted to CoolRobot, how the data is computed and what the robots answers to certain requests are.

5.3.1 Establish and terminate a connection

Before attempting to connect Cool Robot and a remote station all the hardware should be set up properly. At first, the radio modem must be connected to the internal power supplies within the robot. There is one connector for the housekeeping power supply which provides the radio modem with +10VDC. The radio modem used with a laptop as control station and both radios run on batteries, the modem requires a 9V block battery and the radios need 3 AA 1.5V batteries each. When starting a test run both modems, as well as both radios should be turned on before compiling the software to the Jackrabbit micro controller. The channel used with the radios is not of importance and can also be changed during a run if there is any disturbance on the channel.

As described in chapter 7.4 different versions of the main control program are available for the use with the radio connection. One of them "mainprog_v0.34" (see chapter 7 for detailed description) is totally based on an radio connection. When the program is compiled to the Jackrabbit and the program starts it is checking if the modem is on and if this is true it will try to connect to the remote host by sending the "connect" command once to the modem. The modem will now try to reach the designated remote host for approximately 1 minute. After this time the robot will wait for an incoming connection and do nothing until it detects a connection to the remote host. After a successful connection the robot switches to manual drive mode and can now be driven manually or switched to another drive mode. If the modem was off on program start the controller is waiting until the modem is turned on and performs the same way as if it was on at start up. If a loss of the connection is detected for any reason the robot will stop and wait until the connection is established again by the remote control.

The second version "mainprog_v0.35" is not as reliant on a radio connection as the first one. It is also checking whether the robots modem is on or off at startup. If the modem is off the robot will also stay inactive and wait until it is turned on. After a "modem on" is detected the robot will immediately switch to waypoint following at full speed and start navigating toward the first waypoint. The initial waypoints are stored in a string defined within the main program and are activated one start up of the program (see chapter 7.1 and 7.2). Besides it will act quite similar to the first version of the main routine. It will try to get a connection for about one minute and after that listen for incoming connections. If a connection to the remote host is detected the robot will go on with the waypoint following but it will furthermore send back its navigation data after every successful run through the navigation algorithm. As soon as a connection is established the robot can of course be controlled like in the first program version. The only difference is, if the connection is lost again the robot will go on with the waypoint following instead of stopping and waiting to reconnect again. Thus, using one of the mentioned main routines the robot will always try to establish a connection, as soon as it realizes the radio modem is on. If the attempt is not successful it will listen for incoming connection requests and autonomously recognize if a connection is established or maybe lost again. The operator can easily establish and terminate the radio connection as described in chapter 5.2.1.2. The robot will never terminate an existing radio connection, since there is simply no need for this feature. A connection can only be terminated by the operator if a need occurs. For example if one test run is finished and another program should be compiled to the micro controller, or if the there is a need for recompiling the program an existing radio connection should be terminated by typing <Ctrl> + <c> and <d> <CR> (see chapter 5.2.1.2). This may avoid some hassle while trying to connect again. The point is the modem on the robot will not realize that the connection is lost without failing to send a data packet or the notification from the remote station that the connection is terminated. Therefore it will be confused if there is another incoming connection request from the station it is supposed to be connected to. Clearing this confusion always takes some time, which can be easily avoided by terminating the connection before a restart of the program.

5.3.2 Manual drive mode

The use of the manual drive mode is the ability to maneuver CoolRobot over short distances and in places where high mobility is needed, for example to drive it out of a building or vehicle to an open area where it is able to navigate on its own. Furthermore the ability to drive the robot manually like a remote-controlled car is essential during testing, since it is the only way to make the robot drive over certain obstacles forth and back and repeat this over and over again or just drive straight line to collect current measurements and so on.

The intention was to make the robot driveable like a small remote controlled car. Unfortunately there is no actual remote control with a steering wheel and a throttle but with a notebook attached to the radio modem and radio it is very similar. In the first place Goetz wrote a function to control the robot while it is connected to a computer via the programming cable. The program continuously queries if one of the keys "w","a","s","d" or "q" is pressed and converts the input into commands to the motor controllers. The speed for all four wheels will always be between +100% and -100% and the speeds of front and rear wheels of one side will always be equal.

w	increase speed by 10% of full speed
s	decrease speed by 10% of full speed
a	turn to the left (decrease speed of the left wheels by 10% and increase speed of the right wheels by 10%)
d	turn to the right (increase speed of the left wheels by 10% and decrease speed of the right wheels by 100%)
q	stop (put the wheel speeds to 0 in 10% steps every 100ms)
p	switch to waypoint following at full speed (short cut for command "$CRCMDMANDM" - see table 5.15)

Table 5.13: *Control keys for manual driving.*

Within the next logical step this principle was adapted to wireless solution as soon as the radio link was available. Since it is very inefficient and slow to send every typed character on its own a arbitrary long series of characters can be typed an sent to the robot by pressing carriage return <CR>. The string will be computed character by character and the motor speeds are

updated after every valid controll character. If some character, other than w,a,s,d or q is typed it is simply ignored. For example if the robot is standing with all motor speeds set to zero percent the string "wwwwaa" will force it to accelerate in steps of 10% up to 40% and then take a left turn by decreasing the left wheel speeds by 20% and increasing the right wheel speeds by 20%. To keep track of the actual motor speeds the robot sends them back to the base every 10 seconds.

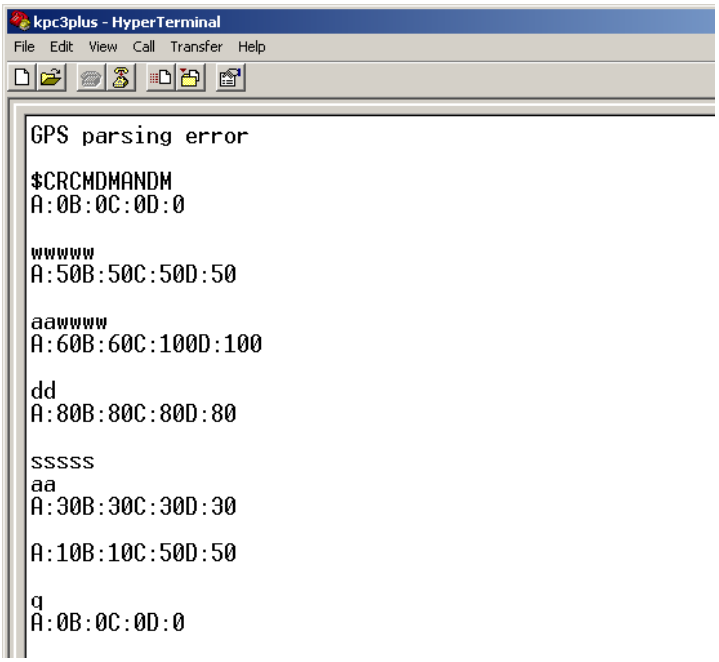


Figure 5.19: *Screen shot of Hyperterminal while in manual drive mode*

The interval for the motor speed sending is intentional chosen quite long to keep the data traffic low and guaranty that commands to the robot are delivered as fast as possible. When Cool Robot resides in manual drive mode it will only move if an radio connection is established and if the connection is lost the robot will stop immediately after it realizes the disconnection. This takes about 60 seconds, because the modem resends packets for this time before the connection is determined as lost. Besides it is not possible to access the manual drive mode without an active radio link. One additional controll key is implemented in the actual version of the manual drive mode. By sending a "p" character, the robot stops immediately and switches to waypoint following at full speed. Normally drive modes are switched by another command as described later on, in this special case I implemented some kind of hot-key for the navigation testing.

5.3.3 Waypoint following

During waypoint following at full or partial speed the movement of the robot cannot be influenced, since it is navigating on autonomously. It is only possible to switch to another drive mode, i.e. from waypoint following at full speed to partial speed, to reduce the robots speed or to the manual drive mode to controll Cool Robot completely manual. Thus, there are no commands to control the robot in general. Besides from that the robot will send all important navigation data back to its base if an active radio connection is existent. This data is condensed into one fairly long string. Every bit of data is divided by the next by an abbreviation of its meaning and ":" separators. The complete datastring looks like the following example:

```
gps:$GPRMC,183137.00,A,4336.5477,N,07207.4734,W,1.0,
339.5,260205,,*25:aw:4336.600002,N,727.800000,W:bp:
4336.551742,N,727.555389,W:cp:4336.547702,N,727.473400,
W:dw:0.448103:bw:282.402374:dbp:0.111044:bbp:0.111044:
cd:0.022833:cb:354.567535
```

The meanings of the abbreviations are as follows:

gps	contains the complete string as it was received from the GPS unit
aw	shows the active waypoint the robot is heading to
bp	shows the active basing point the robot is heading to
cp	shows the current position of the robot
dw	contains the current distance to the active waypoint in kilometers
bw	contains the current bearing to the active waypoint in degrees
dbp	contains the distance to the active basing point in km
bbp	contains the current bearing to the active basing point
cd	means current distance - traveled since programm start
cb	means current bearing clockwise counted from north

Table 5.14: *Components of navigation data string.*

Such a set of data is approximately 235 characters long which equals 235 Bytes. Since the maximum amount of data the modems can handle in one data packet is 256 bytes each of

those data sets fits within one packet and the transmission takes round about 2 seconds. The robot is sending this data once after every completed run through the navigation algorithm. Since it takes something between 5 and 20 seconds for one complete navigation step, including the turn the robot takes for its course correction, there is enough time to send data packets of this size once every step.

5.3.4 Other commands and functions

Irrespective of the drive mode there is always the possibility to send new waypoints to the robot, or request its current status or some of the stored data. One of the most important features within the communication topic is transmitting new waypoints to the robot and by determining the robot's future route. To send the robot one or more new waypoints a simple string must be send, containing the number of waypoints send in this packet and the waypoint data. To be able to process all incoming data as fast and secure as possible I figured out that all the commands used within the data transfer, except the command strings for the manual driving, should have a certain structure and an equal header. Since the appearance of such a header is not of significant importance I decided to use a $ character followed by the characters "C" and "R" as they are the initials of CoolRobot. This pre-header is followed by three further character which indicate what type of data follows or respectively what kind of command is received. New waypoints are indicated by the characters "WPT". The header is then followed by a comma (","), the number of waypoints to follow and another comma. The waypoint data is subsequently attached, every waypoint must be divided from the next by another comma and the waypoints must be of the following syntax: `ddmm.mmmmLdddmm.mmmmB`. The first 9 characters determine the latitude in degrees (dd) and minutes (mm.mmmmm) and the tenth character holds the information whether the waypoint is in the northern (N) or southern (S) hemisphere. It is almost the same with the longitude data, three characters for degrees (ddd) seven characters for minutes (mm.mmmm) and one for eastern (E) or western (W) direction. Thus, a full example will look like this:

```
$CRWPT,2,4338.1000N07209.1200W,4337.9200N07208.7600W,
```

The last comma is not neccessary but it also wiil not bother the function processing this input. If the waypoint string was send and received correctly CoolRobot will answer how much new waypoints it received and stored. Alternatively if any error occurred within the waypoint string the robot will respond only with the number of waypoints it received correctly. For example if 5 waypoint were sent and there is a problem within the third waypoint the robot will only store the first two correct waypoints and report that it successfully received 2 waypoints.

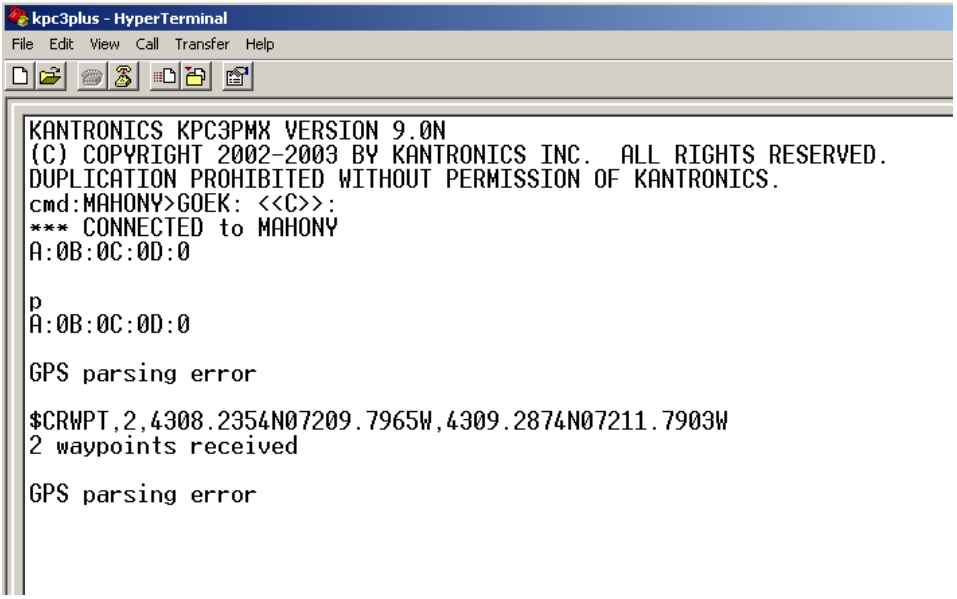


Figure 5.20: *Screen shot of Hyperterminal: sending waypoints*

For the testing it might also be important to manually switch between different drive modes back and forth. Therefore a set of commands is implemented to enter every of the four implemented drive modes independent from the robots actual drive mode. The commands consist of the header "$CR" plus three characters indicating a command "CMD" and code of five characters for each drive mode. The full command sequence for each drive mode is show in the following table.

"$CRCMDMANDM"	to enter the manual drive mode
"$CRCMDWPFFL"	to switch to waypoint following at full speed
"$CRCMDWPFPT"	to switch to waypoint following at partial speed (60%)
"$CRCMDGOTST"	to switch to the special drive mode when the robot got stuck

Table 5.15: *Overview of commands to enter/switch drive modes.*

The last two commands for a status request and a data request are already implemented in the communication code but not 100% functional at the moment. Both of them cause an answer from the robot but act more as an example for further use then as real fully functional features of the communication. To originate a status request the command string "$CRSRQ" must be send to the robot and it will answer this request with a string containing only the number of the actual drive mode it reside in plus the actual set motor speeds.

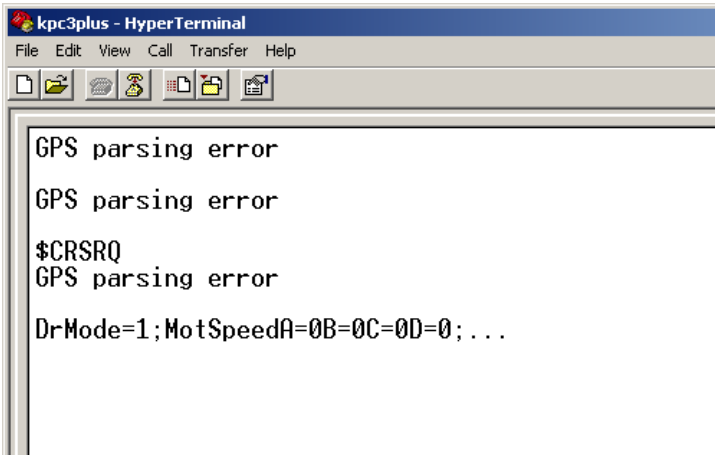


Figure 5.21: *Screen shot of Hyperterminal: requesting CoolRobots status*

A data request, performed by sending "$CRDRQ", is a little bit more functional, since on a data request the controller will try to open the logfile and read back the last 32bytes to send them back to the user (described in detail in chapter 7.3.3). If the logfile cannot be opened, because it does not exist, there is no data or less than 32 bytes to read back the answer will be "could not open logfile" respectively "no data found".

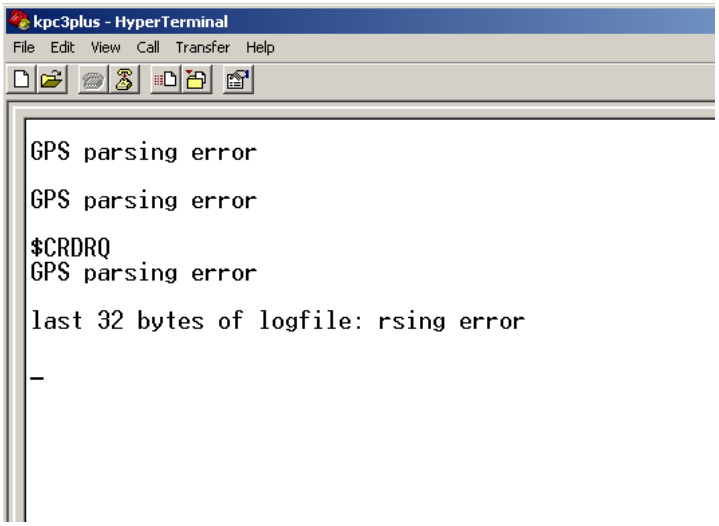


Figure 5.22: *Screen shot of Hyperterminal: requesting data from CoolRobot*

These are all communication related commands and features actually included with the CoolRobots main program. For a short summary on the reliability and the test results with CoolRobot and its communication system see chapter 8.4.

Chapter 6

Data storage

Since CoolRobot is designed to act as a multi purpose mobile platform for scientific measurement instrument in the Antarctic region one of the main issues within the future missions will be to collect and record data of the scientific payload. Most of this scientific data will be analog output voltages from various sensors. To record this data the robot will be equipped with a Campbell Scientific CR1000 datalogger which just arrived and is now available for first tests.

Figure 6.1: *Picture of the Campbell Scientific CR1000 datalogger*

Besides this scientific data produced by the carried payload, the robots internal sensors and the control algorithm itself will produce a lot of data too. Especially within the robots first mission and during the test runs at Dartmouth and later on in Greenland this sensor data is

of special interest, since the whole behavior of the robot can be reconstructed and analyzed using this data. Interesting are for example the currents the motors draw as well as the overall current from the batteries while traveling along differently shaped paths to prove the existing estimates for the power consumption. On the other hand a lot of the data used within the navigation algorithm is of big interest for later analysis of the way the robot traveled. At the moment it is needed to prove the navigation algorithm is working correct and stable.

6.1 Storage and retrieval of internal sensor data

The alternative to using a datalogger is the internal flash memory of the micro controller. The DynamicC software provides a library which allows to build a file system known as file system mkII or FS2 within the Jackrabbit's first or second flash memory. Depending on the micro controller used the second flash may or may not be available. The Jackrabbit RCM3110 core module provided with the evaluation board has got one flash memory of 256k Bytes whereas the RCM3100 core module has twice as much flash memory divided into two separate chips. Both of the memory sections can be used as code memory and as memory for the file system, but normally the first flash is used as code space and the second flash is reserved for a file system. There is a possibility to use parts of the first flash (especially if it is the only flash device) to install a file system but since the software for the CoolRobot uses program space of more than 130k there is not much space left to store data.

Figure 6.2: *Picture of Z-Worlds RCM3100 core module*

We switched to the RCM3100 processor and now have up to 256k space for a file system and a lot of space for further software enhancements. This theoretical value cannot reach 100% because some of the space is used internally for the data management of the file system. The maximum number of files to be used as well as the desired logical sector (LS) size limit the actual space available. A few big files are more efficient than a lot of small files because every file needs one sector for its metadata, which is data used by the file system managment and therefore more files equal more memory used for the metadata. The LS size also got a big influence on the efficiency of the used memory. There is one sample program ("FS2INFO.C") included with the DynamicC package which checks the specifications of all memories attached to the micro controller regarding the filesystem and displays the results as shown in figure 6.3. The test was performed on the RCM3100 board and the second Flash memory is shown as device number 1, device class byte-writeable. Device number 2 is the 512k Byte RAM memory, the reason why there are only about 128k available for files is that specific areas of this memory are used by the Jackrabbits BIOS.

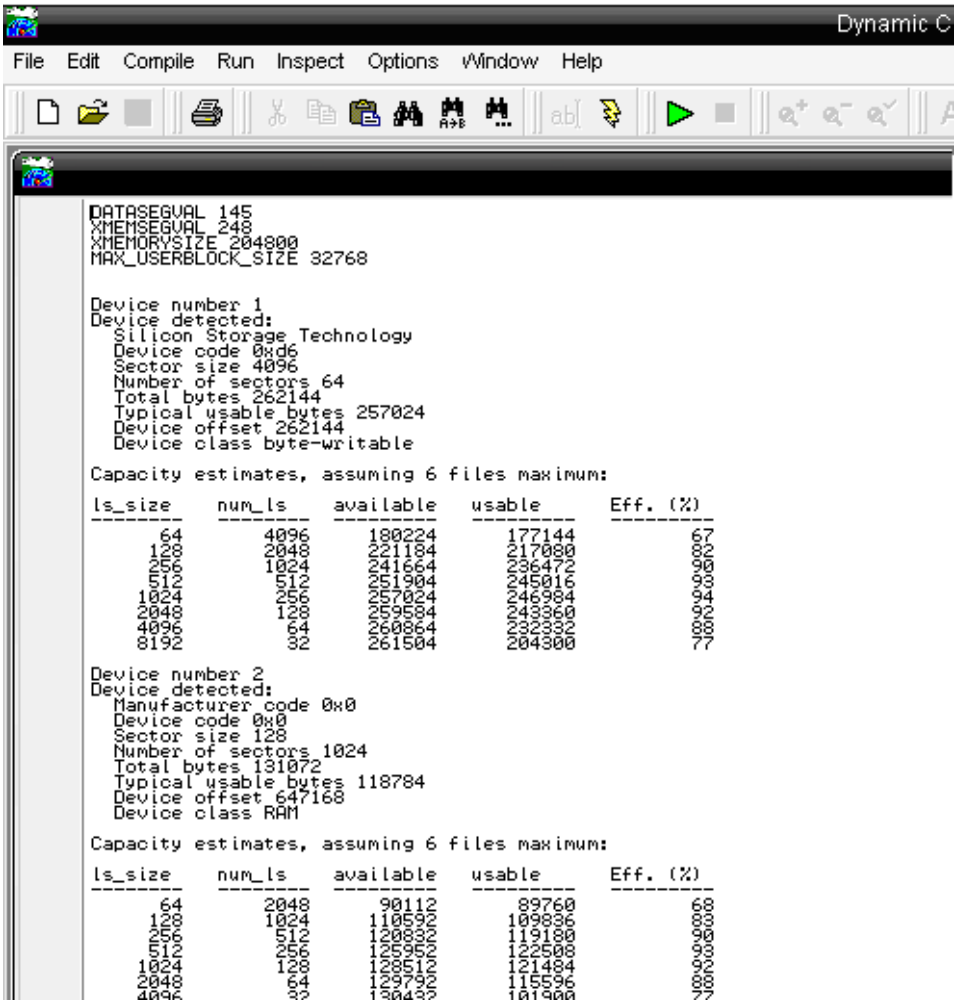


Figure 6.3: *Screen shot of FS2 sample program showing specifications of the Flash memory*

According to those results I set up the file system in the second flash with the recommend parameter LS size at 1024 Bytes for maximum efficiency. I wrote a test program to create a testfile and fill it with virtual navigation data. When reading the file back with a small program I wrote ("2ndFlashReadLogFile.C") I came up with a maximum file size of 256.396 Bytes in two independent test runs. This is a bit more than estimated because I only used one file to store all the test data and the estimate was calculating with 6 files.

To get an image of what we are able to record with this amount of memory, lets take the actual navigation process and the data recorded or sent to the base while navigating. As mentioned in chapter 5.3.3, one complete set of navigation data, including the original string received from the GPS unit, the waypoint, basingpoint, both current points and all of the calculated distances

and bearings sums up to round about 235 characters which equals 235Bytes depending on the actual values carried. Considering the available memory of slightly above 253kBytes we are able to store an estimate of 1075 sets of data. Assuming an average time between the storage of two data sets of 33 seconds (30 seconds from one navigation cycle to the next plus the time the turn for the course correction takes, estimated to 3 seconds in average) the total recordable time would multiply to:

$$1075 \cdot 33sec = 35475sec = 519.25min = 9.85h$$

Thus, we are able to record nearly ten hours of continuous waypoint following in detail. This time grows even bigger considering the original GPS string, as well as some other recorded values, are not essential for later analysis. Just cutting down on the original GPS string saves us 52Bytes, which drops the size of one data set to only 185Bytes. Doing the math again we should be able to store just around 1365 data sets equivalent to:

$$1365 \cdot 33sec = 45045sec = 750.75min = 12.51h$$

A gain of more than 2.5 hours. This time can be grown easily by cutting some data that is not quiet essential for the analysis of the the robot's behavior. For the tests in Greenland the datalogger might be available to store all this data, but just in case it is not ready the flash file system might be a sufficient way to collect data from test runs of nearly one day. Or it can be used as a spare system. Assuming that the navigation is working fine, there might be no need to record all the navigation data or even no navigation data at all. Besides there is always the possibility to send this data to the base station or operator and record it locally on the PC for later analysis. This would allow for the storage of all interesting sensor data in the flash file system, clearly arranged in different files for each kind of data.

The data we are recording is basically the same as which is sent back via the radio connection when CoolRobot is following waypoints. We wanted to be able to record the navigation data without the need for a radio link. Furthermore the file system offers the possibility to log all other relevant data produced while CoolRobot is operating, like currents, wheel speeds, tilt angles and so on, once the ADC is running. To keep all the collected data more concise and make the analysis easier, different kinds of data can be stored to different logfiles. At the moment there is only one logfile used to record the navigation data but as soon as the the new

analog to digital converter is running, there will be a demand to record motor currents while the robot is running around. It would be easy to create a second logfile for all kinds of current and voltage readings by just duplicating and slightly modifying existing code.

Instructions for setting up a file system in the flash memory using DynamicC are described in detail in chapter 7.1 and 7.2. For the basic file related tasks, like reading from the file and writing data to it some functions provided by DynamicC's library "FS2.LIB" are essential.

fopen_rd(File, FileNumber)/fopen_wr(File, FileNumber) simply opens the specified file either in read mode ("fopen_rd") or write mode ("fopen_wr"). A file cannot be opened for both, reading and writing at the same time.

fseek(File, Where, Whence) is used to set the current read/write position of the file. The parameter "Whence" defines relative to which point of the file the position will be set: SEEK_SET is relative to the beginning, SEEK_END to the end of the file, SEEK_CUR starts at the current position and SEEK_RAW is a special case of seek end which allow to write data after the end of the actual file. The parameter "Where" is used to add an positive of negative offset to the position. For example `fseek(&testfile,10,SEEK_SET)` will set the the read/write position to the tenth byte of the file called testfile.

fread(File, Buffer, Length)/fwrite(File, Buffer, Length) are very similar in their use. Both functions will read/write the number of bytes specified in "Length" from/to logfile to/from the character buffer pointed to by "Buffer". The reading respectively writing starts at the position set by "fseek()".

fclose(File) closes an opened file.

As an example, the following lines will open a file called "testfile" with the file name defined in `TEST_FILE_NAME`, append the character string stored in the variable `buffer` to the file and close the file after writing.

```
fopen_rd(&testfile, TEST_FILE_NAME);
fseek(&testfile, 0, SEEK_END);
fwrite(&testfile, buffer, sizeof(buffer));
fclose(&testfile);
```

In the shown case, no error handling is performed, which means there is no guarantee that the data was really written to the file. Error handling is pretty easy with those functions, since all of them return integer values that indicate whether the operation was successful or not. Those return codes can be stored to a arbitrary integer variable and checked using an if-statement.

```
rc = fopen_rd(&testfile, TEST_FILE_NAME)
if(rc == 0)
{
  ...

else
{
 ...
```

If "testfile" was opened successfully `rc` will hold a zero and the code within the if-statement will be executed. Otherwise the code within the else-statement, maybe some error handling or just a prompt that an error occured, will be executed.

For further possibilities on using DynamicC's flash file system the DynamicC user manual chapter 11 is recommended as well as the DynamicC function reference for more detailed information on all available functions.

6.2 The Campbell CR5000 and CR1000 dataloggers

All the digital data produced by the Jackrabbit's control algorithm is not supposed to be stored on a datalogger during the ongoing test runs for two reasons: first the CR1000 datalogger which is supposed to be used has only just arrived and has not been tested in any way. And second is the difficulty in communicating between Jackrabbit micro controller and available CR5000 datalogger. Both units have the ability to exchange data via a RS232 serial port, but the problem is it is unknown how the datalogger communicates exactly and what kind of commands are needed to control it. There is software provided with the CR5000 datalogger called PC9000 to control it via a personal computer furthermore an extensive manual which describes how to handle and program the CR5000 but not one sentence about commands to control it using a micro controller or something equal. It is not essential that the datalogger

can be controlled by the micro controller, but it would score a lot of benefits. It would achieve the possibility to start, stop and run different recording programms on the datalogger during one journey furthermore the communication and data exchange between micro controller and datalogger should be much easier.

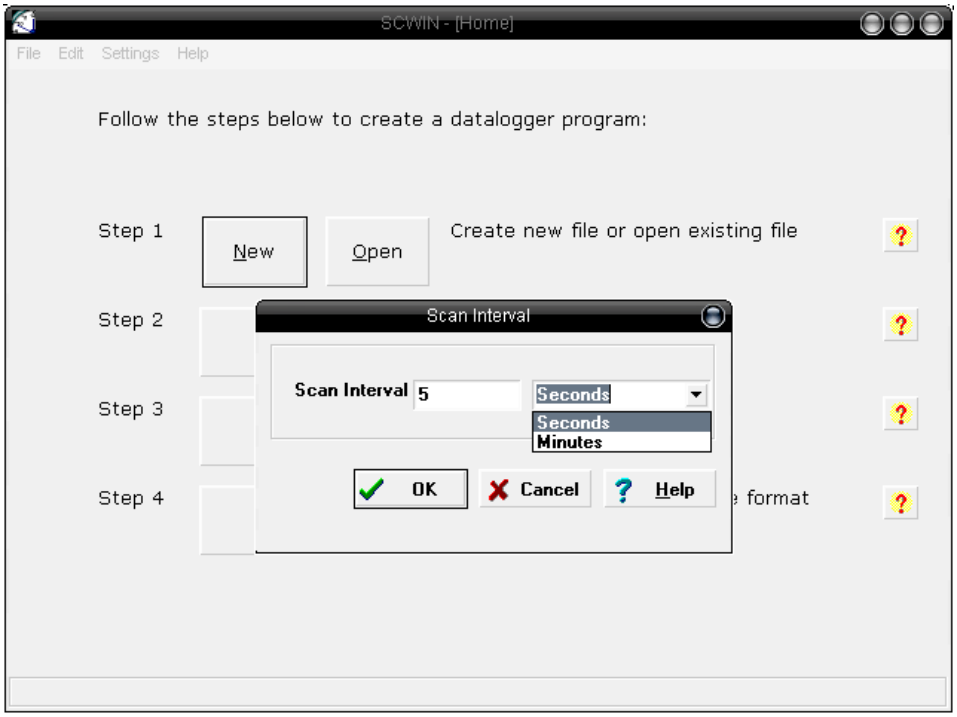


Figure 6.4: *Screen shot of "Short Cut" first step: edit measurement interval*

According to the datasheet of the CR1000 datalogger and its manual the serial communication is supposed to be much easier in this product generation. Furthermore it is much easier to build simple programs for sensor readings, since in addition to the "CRBasic" editor, also included with the CR5000, there is a wizard program called "Short Cut" included with the CR1000s "LoggerNet" software package. "CRBasic" is a "BASIC"-like programming language used to create programs for the Campbell dataloggers.

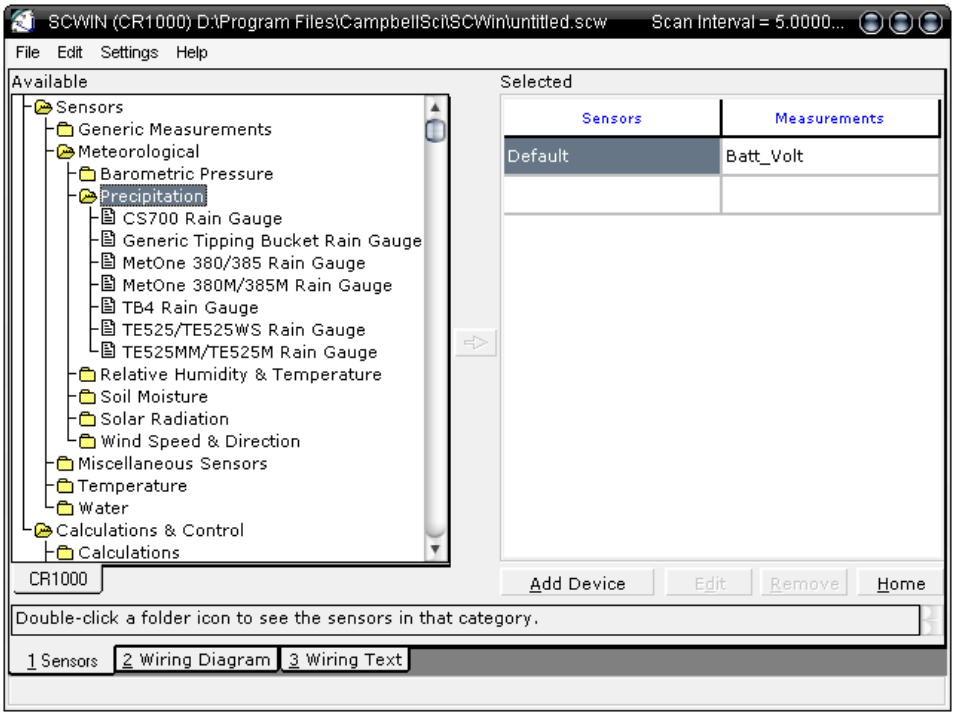


Figure 6.5: *Screen shot of "Short Cut" second step: choosing sensors*

"Short Cut" allows to select the interval of the measurements, different sensors and the tables the data should be stored to and "Short Cut" builds the program for the specified datalogger type. This program file can be edited and extended afterwards using the "CRBasic" editor. Thus, "Short Cut" makes it pretty easy to create routines for the basic measurements and also collecting data from sensors using RS232 serial communication.

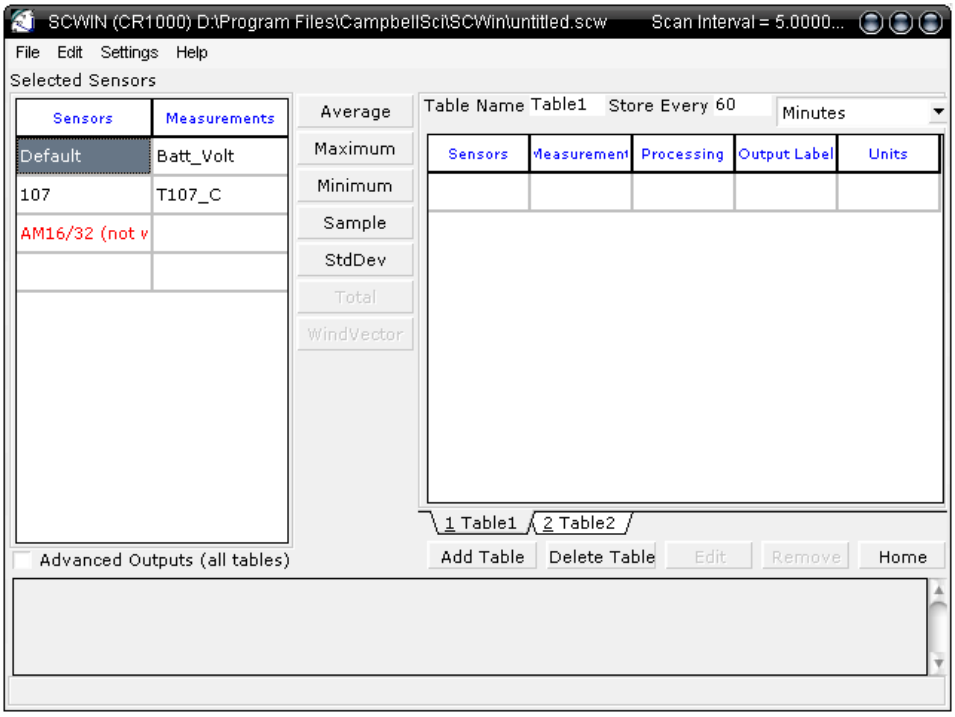


Figure 6.6: *Screen shot of "Short Cut" third step: select tables*

There are actually two possibilities to send and receive data via the serial port from within a running program on the CR5000/CR1000. The first one is via a CAN-bus system which is to difficult and extensive in code space to implement it on the CoolRobots micro controller in addition to the existing software. Another way might be through two commands for input from the CR1000s RS232 serial and input/output on the CS I/O port:

SerialInput (Dest, Max_Values, Termination_Char, FilterString)

The "SerialInput" instruction is used to measure a serial sensor connected to the datalogger's RS232 port. This instruction can be included within every cycle of the measurement program to check for an input character string and store it to a predefined array if something is received.

The parameters of "SerialInput" are:

Dest - The Dest parameter is a variable array in which to store the values received from the serial sensor. The array should be dimensioned to the size of Max_Values.

Max_Values - is the maximum number of characters that will be transmitted by the sensor between the filter string and the termination character.

Termination_Char - is the character that will be used to mark the end of the transmitted string. This number must be less than 128.

FilterString - is a string of characters used to mark the beginning of the data transmitted from the serial sensor.

GOESData (ResultCode, Table, TableOption, BufferControl, DataFormat)

The "GOESData" instruction is intended to be used with a SAT HDR GOES satellite data transmitter. The data transfer to the transmitter can occur via the datalogger's CS I/O port only. If the datalogger is sending a command, all further tasks will be executed only after a response is received. The big problem with this instruction is that it uses the CS I/O port instead of the RS232 port like "SerialInput" and it might block the measurement routine if there is no answer to a command.

The "GOESData" instruction has the following parameters:

ResultCode parameter is a variable that holds a result code indicating the success of the program instruction. The result codes are as follows:

Code	Description
0	Command executed successfully
2	Timed out waiting for STX character from transmitter after SDC addressing
3	Wrong character received after SDC addressing
4	Something other than ACK returned when select data buffer command was executed
5	Timed out waiting for ACK
6	CS I/O port not available
7	ACK not returned following data append or overwrite command

Table 6.1: *Possible values for the ResultCode.*

Table The Table parameter is the data table from which record(s) should be transmitted.

TableOption determines which records should be sent from the data table.

0 = send all records since last execution;

1 = send only the most recent record stored in the table.

BufferControl is used to specify whether the ramdom or self-timed buffer should be used and whether data should be overwritten or appended to the existing data. The data stored in the self-timed buffer is will be transmitted at a predetermined time frame only and the data is erased from the transmitter buffer after each transmission. Data in the random buffer is transmitted immediately after a threshold has been exceeded and the transmission will be repeated randomly to insure it is received. Data in the random buffer must be erased using buffer control, code 9, after random transmissions are finished. A numeric value is entered for this parameter:

Code	Description
0	Append to self-timed buffer
1	Overwrite self-timed buffer
2	Append to random buffer
3	Overwrite random buffer
9	Clear random buffer

Table 6.2: *Possible values for BufferControl.*

DataFormat is a numeric value used to define the format of the data sent to the transmitter.

Code	Description
0	CSI FP2 data; 3 bytes per data point
1	Floating point ASCII; 7 bytes per data point
2	18-bit binary integer; 3 bytes per data point, numbers to the right of the decimal are truncated
3	RAWS7; 7 possible data points for total rainfall, wind speed, vector average wind direction, air temperature, RH percentage, fuel stick temperature and battery voltage
4	Fixed decimal ASCII xxx.x
5	Fixed decimal ASCII xx.xx
6	Fixed decimal ASCII x.xxx
7	Fixed decimal ASCII xxx
8	Fixed decimal ASCII xxxxx

Table 6.3: *Possible values for DataFormat.*

Both commands are intended to be used with sensors that use serial communication to output their measurement data. The problem herein is that the datalogger and micro controller are not able to establish a real communication using those commands, there is no guarantee that data is synchronized at the datalogger and is stored correctly. The other way around there is no possibility to request a certain section of the stored data, since the datalogger is only intended to controll sensors using its serial ports not the other way. Storing data from the micro controller to the datalogger should not be a big issue using the "SerialInput" instruction. The other way around I don’t see an obvious possibility to retrieve certain pieces of the earlier stored data from the datalogger to pass it back to the operator via the radio link. The only idea is to find out how exactly the datalogger is communicating with a personal computer and imitate the PC’s behavior with the micro controller.

Chapter 7

Software frame work

The basic idea of CoolRobots Software is one superior main routine with a start up section which is executed only once when the program is started and a big infinite loop that executes all subordinated functions and algorithms according to the present demands pictured by the sensors.

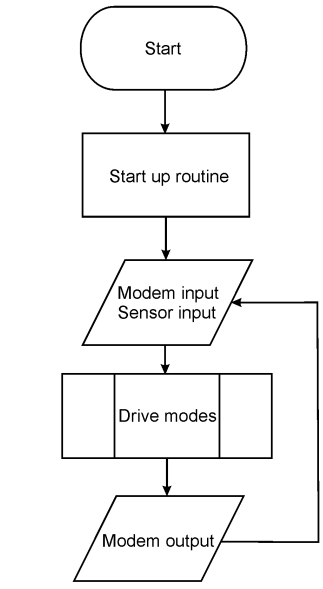


Figure 7.1: *Rough schematic of CoolRobots software*

What exactly is executed on every run through the loop depends on certain global variables which can be changed by the functions that compute input data. Thus, on every cycle off the

main loop the parameters are set for the next cycle. As shown in figure 7.1 the main program constist four major parts:

(1) The startup routine,
(2) a block for the modem input,
(3) the main control section
(4) and a block for the modem output.

The modem input/output blocks and the main controll section form the main loop of CoolRobots control program. The reason they are listed separately is they are separated within the code too. They are all placed within their own "Costate" which allows those three tasks to run seemingly parallel. DynamicC is capable of some kind of multithreading which they call cooperative multi tasking.

> "Cooperative multitasking is a way to perform several different tasks at virtually the same time. An example would be to step a machine through a sequence of tasks and at the same time carry on a dialog with the operator via a keyboard interface. Each separate task voluntarily surrenders its compute time when it does not need to perform any more immediate activity."

They following sections will introduce the reader to the status quo of the CoolRobot main program "mainprogV0.34" and the distinctions to other versions modified to fit different testing requirements. The features of this program are fully implemented radio communication, data recording capability within the flash memory and three fully functional drive modes available.

7.1 Definitions, libraries and variable declarations

To keep the program concise and straightforward, almost all of the functions Goetz and I wrote for the control program are grouped together in libraries according to their field of use. Furthermore some of the features, like the filesystem, used within the program are also

provided in libraries with the DynamicC software. Those libraries must be included with the program at the very beginning using the #use instruction and some global parameters must be defined using #define.

```
#memmap xmem

#define FS2_USE_PROGRAM_FLASH 16
#define LX_2_USE  fs_get_flash_lx()
#define MY_LS_SHIFT 9
#define LOG_FILE_NAME (1+LX_2_USE)

#define SPI_CLK_DIVISOR 10

#define EINBUFSIZE 511
#define EOUTBUFSIZE 511
#define CINBUFSIZE 255
#define COUTBUFSIZE 255

#use FS2.LIB
#use GPS.LIB
#use DRIVE.LIB
#use ANALOGIN.LIB
#use RADIOCOMM_E.LIB
#use NAVIGATE.LIB
```

The instruction #memmap xmem allows the use of extended memory (the upper 128kByte of the first flash memory) as code space in addition to the regular code space (only the lower 128kByte of the first flash). This is necessary because the CoolRobot control program in its final version exceeded a size of 128kBytes.

The first 4 #define statements determine some parameters for the file system used. FS2_USE_PROGRAM_FLASH reserves the specified amount of 4096Byte blocks of the first flash for the file system. To use parts of the first flash for a file system in the "rabbitbios.c" file XMEM_RESERVE_SIZE 0x0000L must be changed to for example to XMEM_RESERVE_SIZE 0xF000L to reserve some of the extended memory (0xF000L equals 61440Bytes). This instruction was used with the Jackrabbit RCM3110 that only got the first flash and is not essential anymore since on the RCM3100 256kBytes of second flash are available. In the next line the function "fs_get_flash_lx()" is used to find out the logical extend number of the second flash and store it to the parameter LX_2_USE. The logical extend is comparable to name or address of the memory device and in our case LX_2_USE = 1, since the second flash memory is detected as device number 1 (see Figure 6.3). The param-

eter `MY_LS_SHIFT` is used to determine the size of the logical sectors (LS) used in the file system. The LS size got influence on the efficiency of the file system and maximum available space (compare Figure 6.3). This parameter can take values of 2^x Bytes. In our case the exponent is chosen to be 9, which equals a LS size of 1024Bytes and achieves most efficiency for our file system. The last of those four lines defines a "file name" for our logfile. In FS2 the actual file names are numbers between 1 and 255. The file name for our logfile is set to `1+LX_2_USE = 2`.

The `SPI_CLOCK_DIVISOR` devides down the internal clock of the micro controller by the specified factor (here: 10) for the use as serial I/O clock.

The next four lines only set the size of input and output buffers of the serial ports C and E. The size must be defined to a value of 2^{n-1} Bytes otherwise they are defaulted to 31Bytes and a warning is displayed when compiling the program. For our application the buffer size are quiet big with 511Bytes and 255Bytes because the serial inputs form the modem (serial port E) and the GPS unit (serial port C) are character strings with sizes up to 256 characters respectively around 100 characters.

The included libraries listed in the next 5 lines. Sometimes it is important to include the libraries in the right order, for example the libraries "NAVIGATE.LIB" and "RADIOCOMM_E" are using the data structure `GPSPosition` which is defined in the "GPS.LIB". Thus it is important to include the "GPS.LIB" before the others are included, or the compiler will complain about dozens of errors, because the data structure is used before it is defined. A complete list of the used libraries and the functions they provide can be found in appendix A Table A.1.

```
const char wp_string[] = "$CRWPT,3,4336.6000N07207.8000W,
4336.9600N07208.0400W,
4336.4800N7207.3800W";
const int motor_speed_increment = 10;
const int angle = 20;
char in_string[256];
char buffer[256];
char buf[1024];
char out_string[256];
char in_stri[128];
GPSPosition wayp;
GPSPosition test_point;
GPSPosition wp_list[100];
File logfile;
```

```
int wp_count;
int wp_active;
int wp_rcvd;
int wp_start;
int drive_mode;
int status_modem;
int send_event;
int motor_speed[4];
int lp_count;
int tm_count;
int FSrc;
float dis_bp;
```

This part of the code declares all the global variables used within the program. Global variables can be read and changed by every function within the program. Thus it is possible to pass values back and forth between functions called either libraries or the main routine. A good example for such a variable is the integer `drive_mode`. It is used within the main routine to switch between the different drive modes, for example `drive_mode = 1` will run the algorithm for the drive mode waypoint following at full speed. The variable can be changed within the algorithm of one drive mode to exit it and enter another drive mode on the next cycle, or it can be changed by the function that computes the modem input if the command for certain drive mode is received. For example "$CRCMDMANDM" will set `drive_mode = 5` and the manual drive mode will be entered on the next cycle. The purpose of almost all global variables is described within a comment next to the variable in the actual code of the "MAINPROGV0.34.C".

7.2 Start up sequence: initializing of variables, file system and serial ports

The program itself starts with the `void main() {` statement and the first things we need to do before any function is called is an initialization of the variables. This is necessary because with the declaration of a variable only an logical address is associated with the variable name, but the actual memory at the given address is not formated, so the data of an earlier program still exists and fills the variable with unknown values. Therefore all variables should be set to a discrete value before they are used by any function. Of special importance is for example

the setting of the motor speeds and the sending to the motor controllers using the function "UpdateMotorOutput()".

```
void main()
{
   status_modem = 0;
   wp_active  = 0;
   wp_count = 0;
   wp_rcvd  = 0;
   wp_start = 0;
   send_event = 0;
   tm_count = 0;
   drive_mode = 5;
   dis_bp = 0.1;

   motor_speed[0] = 0;
   motor_speed[1] = 0;
   motor_speed[2] = 0;
   motor_speed[3] = 0;
   UpdateMotorOutput();

   str2wayp(wp_string, &test_point);

   memset(buffer, 0x00, sizeof(buffer));
   memset(in_string, 0x00, sizeof(in_string));
```

Another important part is the handling of the waypoints for the navigation algorithm. The waypoints for the CoolRobot consist of GPS coordinates in the structure GPSPosition, which is defined in GPS.LIB. To store a bunch of waypoints for a complete trip there is an array of GPSPosition structures called `wp_list` and it can hold up to 100 waypoints. The function "str2wayp(*char, GPSPosition)" is a helper function to translate a character string of a certain shape (see section 5.3.4) into waypoints of type GPSPosition and stores them into the `wp_list`. The `&test_point` GPSPosition is only some used to temporarily store the waypoint data before it is written to the `wp_list`. To keep track of the number of waypoints stored and which waypoint the robot is actually heading to two integer variables are used. The first `wp_count` holds the total number of waypoints stored within `wp_list` and the second one `wp_active` indicates the waypoint actually heading to. It is important to know that `wp_active` starts counting from 0. So number 0 is the first way point, number 1 is the second and so on.

The drive mode is initially set to manual drive mode (`drive_mode = 5`), the status of the modem is determined as "off" (`status_modem = 0`) and `send_event = 0` represents "nothing to send".

Command	Value	Meaning
`status_modem`	0	modem off
	1	modem on, disconnected
	2	modem on, connected to remote host
`drive_mode`	1	waypoint following full speed
	2	waypoint following partial speed
	3	"got stuck" mode
	5	manual drive mode
`send_event`	0	nothing to send
	1	number of waypoints succesful received
	3	answer to status request
	4	answer to data request
	5	send back navigation data

Table 7.1: *Overview of status variables.*

The following section deals with the initialization of the filesystem and the creation of the logfile. The first piece of code only checks if the storage device defined in `LX_2_USE`is available. If not the program will be terminated with exit code 1.

```
  if (!LX_2_USE)
  {
printf("The specified device (logic extent #%d)
does not exist.  Change LX_2_USE.\n",(int)LX_2_USE);
exit(1);
}
else
  {
printf("Using device logic extent (LX) #%d.\n",
(int)LX_2_USE);
  }
```

Now the filesystem will be initialized using the function "fs_init(0, 0). The first parameters for this function must be zero and the second one is ignored anyway, thus they don’t change anything. If the file system could not be intialized for any reason the program will be terminated with exit code 2.

```
  FSrc = fs_init(0,0);
if (FSrc)
  {
printf("Could not initialize filesystem, error number %d\n", errno);
exit(2);
}
```

After the successful initialization the file system can be formated using "lx_format(LXnum, wearlevel) or an existing file system can be reused. If any error occures the program will be terminated with exit code 3. If no errors occur the memory of the logic extend is printed.

```
  printf("Do you want to:\n");
printf("  <enter>       Re-use existing filesystem -or-\n");
printf("  F <enter>     Format the filesystem LX?\n");
gets(buf);

if (toupper(buf[0]) == 'F')
   {
FSrc = lx_format(LX_2_USE, 0);
if (FSrc)
    {
printf("Format failed, error code %d\n", errno);
exit(3);
}
}

   printf("Capacity of LX #%d is approximately %ld bytes\n",
    (int)LX_2_USE, fs_get_lx_size(LX_2_USE, 0, 0));
```

The last step is to create a file using function "fcreate(File, FileNumber)". If the error "File exists is returned the program will ask the user whether the old file should be deleted and a new file created or if the old file should be kept and the new data appended to the existing file. In case of appending the new data to the existing file the program will ask for a separator, which makes it easier to distinguish data of different test runs from each other.

```
fs_set_lx(LX_2_USE, LX_2_USE);
FSrc = fcreate(&logfile, LOG_FILE_NAME);

if (FSrc && errno == EEXIST)
   {
printf("Logfile %d already exists.\n",
(int)LOG_FILE_NAME);
    printf("Delete existing file or apend new
    data to old file?\n\n DELETE? (y/n)\n");
gets(buf);
if (toupper(buf[0]) == 'Y')
```

```
    {
fdelete(LOG_FILE_NAME);
FSrc = fcreate(&logfile, LOG_FILE_NAME);
}
else
{
      printf("Type some seperator:\n");
      gets(buf);
      buf[strlen(buf)] = '\n';
      buf[strlen(buf)] = '\0';
FSrc = fopen_wr(&logfile, LOG_FILE_NAME);
      fseek(&logfile,0,SEEK_END);
      fwrite(&logfile,buf,strlen(buf));
    }
}
```

The error checks always works the same way, all functions used to perform file operations return specific error codes, which are stored in the integer variable `FSrc`. After the execution of a function the return code is interpreted by a "if"-statement. If an error occurred while creating the new file respectively writing the separator to the existing file the program will be terminated with exit code 4. If everything was allright, the file is closed and from now on available for data storage.

```
if (FSrc)
  {
printf("Couldn't create/open file %d: errno = %d\n",
(int)LOG_FILE_NAME, errno);
exit(4);
}
  fclose(&logfile);
```

The last part of the start up section opens the serial ports C and E that are used for data exchange with the radio modem and the GPS unit. The ports are opened using the function "serXopen(Baudrate)" where X can be a letter from A to F for the 6 available serial ports. After opening the ports the read and write buffers of each serial port are cleared using "serXwrFlush()" and "serXrdFlush()". The last few lines represent a test output to the radio modem using "cof_serEputs(*char)", a simple cofunction to output character strings to a serial port. This is used to check if the modem is on or not. If it is on it will respond with an output that indicates that it can not understand the entered command. This answer is received and interpreted by the modem input routine which sets `status_modem = 1` for modem on.

```
serEopen(9600);
serEwrFlush();
serErdFlush();
serCopen(4800);
serCwrFlush();
serCrdFlush();

costate
{
 wfd cof_serEputs("modem test\r");
}
```

7.3 The main loop

The main loop is the heart of the control software since it is the part that is executed all the time when the micro controller is running. The infinite loop itself is started by a "while(1) ... " statement. Everything within the curly brackets is executed repeatedly as long as the value given in the round brackets is different for zero.

7.3.1 The modem input block

The modem input block is the smallest section of the main loop and it only purpose is listening for incoming character strings from serial port E. This purpose is served by the cofunction "cof_serEgets(destinantion, maxCharacters, timeout)". It is waiting for characters received on the serial port and reads them to the variable specified as destination until a carriage return, line feed or NULL character is received or the the specified timeout is reached between two characters. This function is located in an own costate because it blocks all other code within this costate following after this function until it receives a string and returns from execution. If no string is received the function will not return and no other code within this costate will be executed. As described at the beginning of this chapter, different costates are executed seemingly simultaneous because they share execution time. If one costate is inactive because its is waiting for something to do like the "cof_serEgets" wait for an incoming string the next costate will get the available execution time. And so on, until the end of the loop is reached and the first costate is executed again. All cofunctions must be called from a "waitfordone"

(wfd) statement because the execution will restart at the "waitfor" or "wfd" statement it was transfered to the next costate.

```
while(1)
  {
   costate
    {
   wfd cof_serEgets( buffer, sizeof(buffer) - 2, 500);
      if(strlen(buffer) != 0)
      {
       memcpy(in_string, buffer, sizeof(buffer));
        termStr(in_string);
        memset(buffer, 0x00, sizeof(buffer));
        printf("%s\n",in_string);
      } // end if
  } // end costate
```

As soon as the cofunction returns it is verified that there is actually something received and `buffer` is not empty. If there is a non-zero string received it will be copied to the variable `in_string` and then terminated with a carriage return character and a zero character using the helper function "termStr(*char)". After this `buffer` is flushed and the received string is printed to the "Studio" window if the micro controller is connected to a PC and the DynamicC compiler. At the moment almost all important data is printed to the "Studio" window just to be able to keep track of what is going on with the program if desired.

7.3.2 The main control block

The costate for the main control block starts with the function "processModemStr(*char)". This function analyzes the character array `in_string`, which contains the a string received from the modem if there was one received. The first action is a check if there is actually a string stored in `in_string` if not the function returns immediately, the second action is cleaning the string of leading line feeds and "cmd:" prompts using the helper function "clearString(*char)". The function detects if the modem is on, a connection is established or lost and sets the variables `status_modem` to the equivalent value (see Table 7.1). Furthermore it processes incoming commands, like switching drive modes, status and data requests or new waypoints. The variables `drive_mode` and `send_event` are set by this function according to the incoming command line and waypoints are stored in the `wp_list` using the

function "str2wayp(*char, GPSPostion)". All incoming strings that are neither waypoints nor a command or a modem output are ignored, since they are either unimportant or a drive string for the manual drive mode. For more detailed information on this function see the commented code of library "RADIOCOMM_E.LIB".

```
costate
    {
processModemStr(in_string);
      if(status_modem == 2)
      {
        switch(drive_mode)
        {
          case 1:  wp_follow_full();
              break;
          case 2: wp_follow_partial();
              break;
          case 3:  got_stuck(in_string);
              break;
          case 5:  if(strlen(in_string) != 0)
              {
              manual_drive(in_string);
                   }
                   break;
          default: break;
        }
    }
      memset(in_string, 0x00, sizeof(in_string));
    }
```

After analyzing the modem input the actual drive mode is entered but only if there is an active radio connection to the base station (`status_modem == 2`), otherwise no drive mode will be entered and the robot remains inactive. Which drive mode is executed depends of the value of the variable `drive_mode`. A switch-case statement selects the drive mode according to the integer value `drive_mode` carries. The default case is only existent to trap a runtime error if `drive_mode` is for any reason not holding one of the valid values. Important is the "break" keyword at the end of every "case" section, since this keyword performs a jump out of the switch-case statement. If "break" is missing the following case will also be executed, which might lead to fatal errors. The different drive modes are introduced in detail in chapter 4.4. At the end of this piece of code the `in_string` is flushed to prevent the execution of the same command a second time. This would be fatal, especially in manual drive mode, since the last drive string would be used again and again until a new one is received.

7.3.3 The modem output block

The modem output section is quite similar to the main control section, since its main part is also a switch-case-statement that selects what kind of data is sent to the base station if an active radio connection is detected. The principle is the same as with switching the drive modes: depending on the integer value `send_event` holds one of at the moment four available routines for the output is executed. Case one is activated if a number of waypoints is received and stored to `wp_list`. The function "str2wayp(*char, GPSPosition)" increments the variable `wp_rcvd` by one for every waypoint that is stored successfully and initializes the answer by setting `send_event = 1`. The function "sprintf(*char, *char format, parameters ...)" fills a formated string pointed to by format with the given parameters and writes it to a specified character array. In the first case, `out_string` is filled with the string "%d waypoints received", where %d is replace by the value stored in `wp_rcvd`. The `out_string` is sent using "cof_serEputs(*char)" as descirbed earlier. Case 3, the answer to a status request, is basically the same, except another format string and four parameters instead of one. Case 5 can be used by different functions the only have to write whatever they want to send to `out_string` and set `send_event = 5`. At this point of the development this case is used to send all the navigation data produced in the library "NAVIGATE.LIB" once every navigation step. The remaining case 4, the answer to a data request is a little more complex, since it does not only send a fixed string. It will try to open the logfile and read the last 32Bytes of data back to send them back. If there is no actual logfile existing it will encounter an error while opening the file and answer to the request with the sentence "could not open logfile" instead of the last 32 stored Bytes. If the file is opened successfully but there is no data to read, or less than 32Bytes the answer will be "no data found". An important thing detail is the reset of `send_event` to zero at the end of every case. If this reset is missing the same data will be sent over and over again in pretty short interval, which might "jam" the radio connection, due to more traffic the given bandwidth can handle.

```
costate
{
  if(status_modem == 2)
  {
    switch(send_event)
    {
      case 1:   sprintf(out_string,"%d waypoints received\n\r",wp_rcvd);
```

```
            wfd cof_serEputs(out_string);
            wp_rcvd = 0;
            send_event = 0;
            break;
  case 3:   sprintf(out_string,"DrMode=%d;MotSpeedA=%dB=%dC=%dD=%d;
              ...\n\r",drive_mode,motor_speed[0],motor_speed[1],
              motor_speed[2],motor_speed[3]);
            wfd cof_serEputs(out_string);
            send_event = 0;
            break;
  case 4:   FSrc = fopen_rd(&logfile, LOG_FILE_NAME);
            if(FSrc == 0)
            {
              fseek(&logfile, -32, SEEK_END);
              FSrc = fread(&logfile, buf, 32);
              if(FSrc == 32)
              {
                fclose(&logfile);
                sprintf(out_string, "last 32 bytes of
                  logfile: %s \n\r", buf);
                wfd cof_serEputs(out_string);
              }
              else
              {
                wfd cof_serEputs("no data found\n\r");
              }
            }
            else
            {
              wfd cof_serEputs("could not open logfile\n\r");
            }
            send_event = 0;
            break;
  case 5:   wfd cof_serEputs(out_string);
            send_event = 0;
            break;
  default:  break;
}
```

In addition to the switch-case-statement there is a short piece of code within an if-statement which is only active in manual drive mode. The first line is just a time delay of ten seconds using the keyword `waitfor` in combination with the delay function "DelaySec()" which returns a zero until the specified time is elaped. As long as `waitfor` receives a zero the execution will jump out of the costate and the next time execution hits this costate it will directly jump to the `waitfor`, ignoring the code beforehand. This means in manual drive mode, all answering function within the switch case statement are disabled. If there is a need for other answers the whole if-statement can be moved into an own costate after this costate. Only the line "memset(outstring,...)" should be added to this costate too, to avoid problems

when filling the `out_string` again.

```
        if(drive_mode == 5)
        {
          waitfor(DelaySec(10));
          sprintf(out_string,"A:%dB:%dC:%dD:%d\n\r",motor_speed[0],
            motor_speed[1],motor_speed[2],motor_speed[3]);
          wfd cof_serEputs(out_string);
        }
      }
```

The last part of the modem output section is not used to send actual data back to the remote station, but to try to connect to this station, as soon as a "modem on" is detected. Therefore this part is not enclosed in the big `if(status_modem == 2)` statement, it has its own elseif-statement to detect if the modem is on, but not connected (status_modem = 1). In this case the command to connect to the base station is passed to the modem just once, the modem will then try to reach the station carrying the callsign "GOEK" for round about 50 seconds. Limitation to one attempt is made by the second if statement and the counter variable `tm_count`. If the modem should try connect for a longer time this part must be changed slightly. `if(tm_count == 0)` must be changed to something like `if(tm_count <= x)` and a `waitfor(DelaySec(y))` should be added in front of the `wfd` with y somewhere above 50 seconds. The robot will then try to connect for x times and the overall time for the connection attempt is simply $x \cdot y$.

```
      else if(status_modem == 1)
      {
        if(tm_count == 0)
        {
          wfd cof_serEputs("connect goek\r");
          tm_count++;
        }
      }
      memset(out_string, 0x00, sizeof(out_string));
    }
  }
}
```

7.4 Different versions of the main programm

The main program as it is described in this chapter, is only one of a number of different versions and varieties derived from this version. The visualized "mainprogV0.34" combines almost all advances yet made, except the capability of measuring and storing currents. Although the required software is written it is not implemented in this code, because of continuous problems with the MAXIM analog to digital converter.

As mentioned earlier (chapter 5.3.1), the "mainprogV0.34" depends on a active radio connection, nothing will happen without being connected. On the other hand, if the connection is lost for some reason the robot will stop whatever it is doing and remain inactive until it detects a connection again. For longterm tests with the navigation algorithm, where is no need to keep track of the navigation while it is running and only the analysis of the data after the run is important, I changed the existing main program so that it is not as addicted to the radio connection any more.

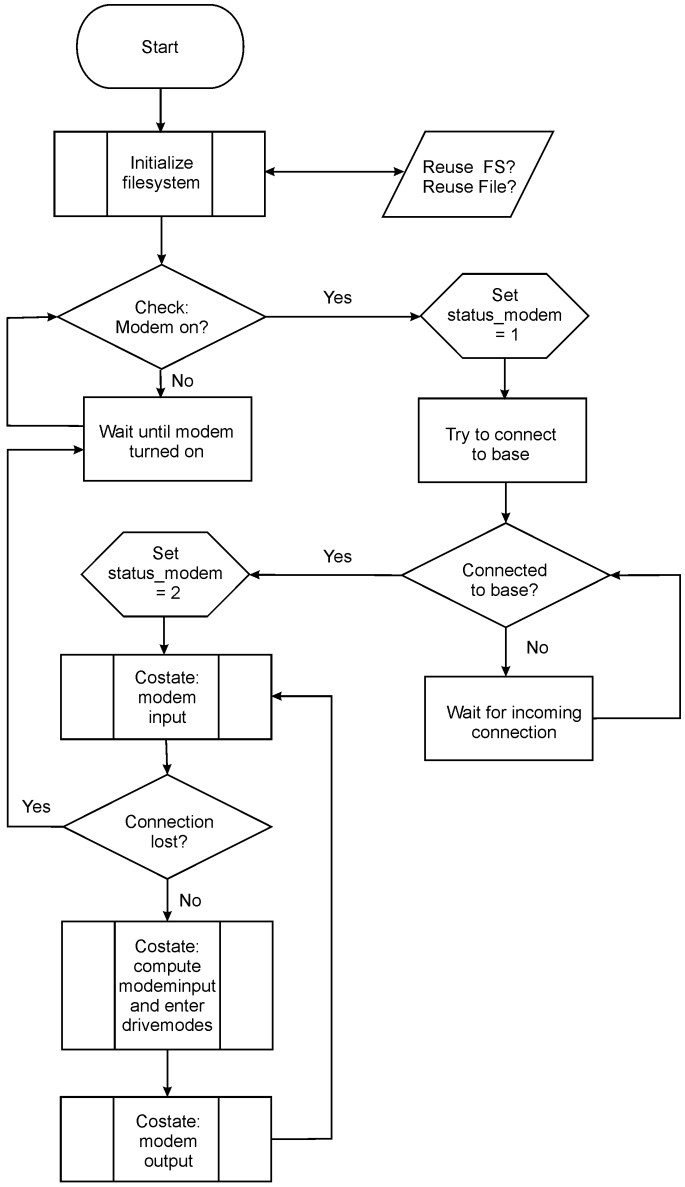


Figure 7.2: *Flow chart of "mainprogV0.34"*

The "mainprogV0.35" has basically all the same features as "mainprogV0.34", like data recording in flash memory, the three drive modes and full radio communication capability. The robot will still be running only if the modem is on, but there is no need for an active radio link. As soon as the program is compiled, the settings for the file system are made and the modem is detected "on", the robot will switch to waypoint following at full speed and start navigating towards its first waypoint. It will try to connect to the base for about one minute and if the connection is successful, the navigation data will be send back to the base in addition to the

storage in flash memory. If it can’t connect it will go on with its navigation, and listen for an incoming connection request. As soon as a connection is detected navigation data is sent back and the robot can be controlled as with the "mainprogV0.34". If the connection is lost or terminated again CoolRobot will go on with navigating, if it was operating in one of the waypoint following drive modes. If the connection is lost in manual drive mode it will reside in this mode but stop the motors, just to prevent uncontrolled driving.

Another slightly different version is called "mainprogV0.24", it is basically exact the same main routine as in "mainprogV0.34", only the ability to store data on the internal flash memory is missing. It is designed for the use with the "smaller" Jackrabbit, which only has 256kBytes of flash memory - not enough to implement a sufficient file system to store serious amounts of test data. All other function are the same, with the tiny difference that no data from the logfile will be sent back on a data request, since there is no actual logfile existent. The answer is always "no data found". To run this variant of the main routine a small change in the code of "NAVIGATE.LIB" must be performed. Lines where the navigation data is written to the logfile (lines 167-170) must be commented out using either "//" at the beginning of every line or enclose the four lines in "/* ... */".

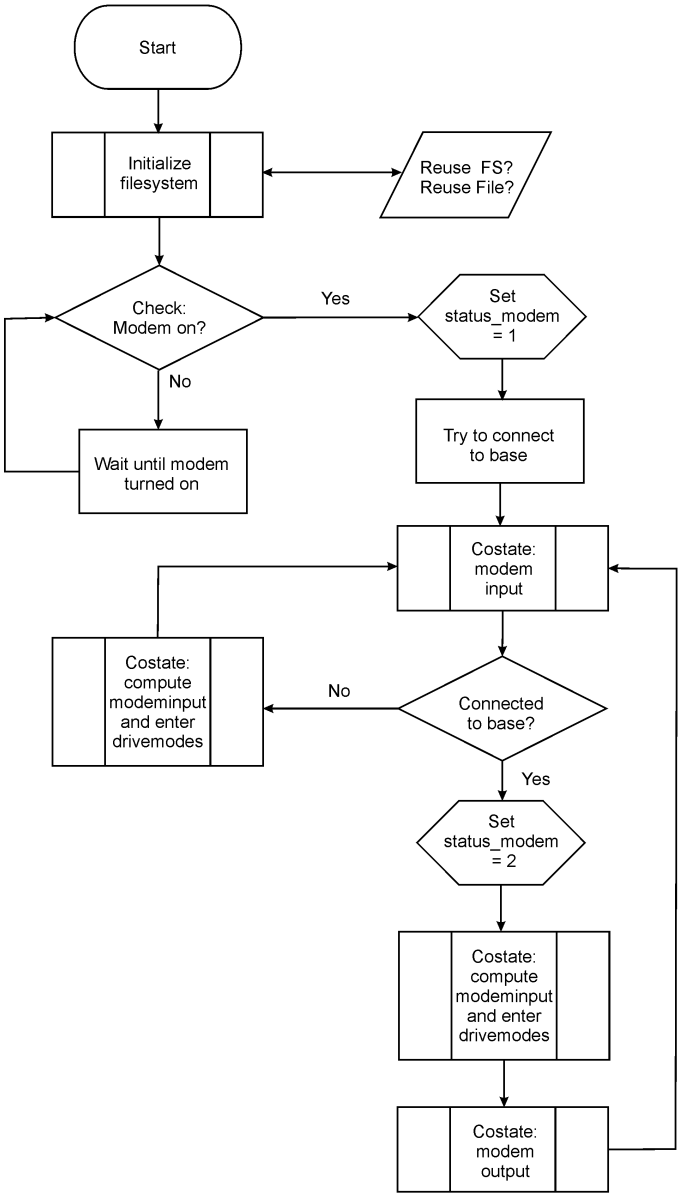


Figure 7.3: *Flow chart of "mainprogV0.35"*

All three versions of the software have been tested, some more and some less. They are all running the way they were supposed to without any runtime or system errors. The first tests were executed using slightly different software, because the development and improvment was still ongoing. As soon as the Jackrabbit core module with the larger memory arrived we did a couple of test runs with the "mainprogV0.34" and few with version 0.35. Unfortunately this core module as well as the evaluation board fell prey to a short circuit and we had to order a new one which only just arrived. Thus, the testing meanwhile had to happen with the

"smaller" micro controller and without the ability to store data locally on the controller, which forced us to use a main routine without the file system feature, version 0.24.

Chapter 8

Results of the moving tests

8.1 GPS waypoint following position and navigation data

During the processing of the navigation algorithm, several errors and bugs occured. Dynamic C has an error handler, which can be programmed and adjusted for the special needs of the Cool Robots project, but that is a great piece of work. The original error handler manages how to handle the errors as for example a calculation of $arccos(2)$. These errors have to be excluded. If one of these errors occurs, dynamic C jumps out of the program at the place where the error occurred without proceeding in the program. That made the Cool Robot drive on with the motor speeds set before that error (in most cases 100%). The robot is now OUT OF CONTROL until the whole program is recompiled. To debug the error, the Laptop has to be connected to the Jackrabbit with the programming cable. Recompiling the navigation program while running behind the robot with the laptop on one arm is not easy. So I made different steps in testing the navigation algorithm and the drive modes "wp_follow_full" and "wp_follow_partial". At first I navigated with the laptop connected to the programming port while driving around in the car. The problems appearing with the infinitesimal distance between the two navigation points were solved by using the "_double precision" library. To check the reliability, I wanted to run the navigation algorithm for hours before taking the robot out. One main field of major interest was the ability of the Cool Robot to climb sastrugi features and even whole sastrugi fields. Therefor the robot was driven in the manual drive

mode to the selected features.

Figure 8.1: *Cool Robot navigating to a waypoint on lake mascoma*

For the testing of the waypoint following drive mode, we took the robot out on lake mascoma near Lebanon (Figure 8.1). The lake was frozen and covered with at least 45 cm of ice. That provided us the opportunity to drive on the lake with the car and stay within the visibility range to the robot and control it if necessary through the radio communication. This chapter describes the testing itself. The necessary preparations, the startup routine and especially the reading and interpretation of the feedback data will be discussed.

8.1.1 Autonomous waypoint following at full speed

The robot is transported without any power supply. Once at the testing area, the batteries and the main housekeeping power distribution board are connected first. Then the jackrabbit, the GPS-receiver and the modem are connected. Before suppling the DAC make sure the output channels are not connected to the motor controllers because they are at -2.9 V if they were shut off from power. The main program may be compiled to the jackrabbit at that point. The motor

speeds are set to zero and are connected to the motor controllers. If both modems are powered up, they will connect autonomously. The connection to the jackrabbit is closed and the modem is connected to the serial port or an alternative port (e.g. USB) and accessed through "Hyper Terminal" (see chapter 5.3.3). The robot can now be controlled through the keypad as it is in drive mode "manual operator". To switch to waypoint following drive mode, the motor speeds **must** be set to zero and "p" has to be hit. Cool Robot now starts to navigate as described in chapter 4.4.1.

Figure B.1 shows a picture of the data evaluation with excel. The test consists of two loops following the four waypoints. The parameters for the navigation algorithm were set to

wp_range	0.025
bp_range	0.030
tm_nav	15
dis_bp	0.1

Table 8.1: *Parameters for waypoint following at full speed 22 mar.*

The Cool Robot had connection to the laptop via radio communication. The data string sent back to the user after completion of a navigation cycle consists the active waypoint, the basing point headed to, the current points and information about all the different distances and bearings. Logged as one string for each cycle in the editor, the data can be imported in excel easily by dividing the different values with a "," and a ":". To graph the position data in a diagram, the longitude and latitude have to be converted. This means, if the latitude direction is "S" or the longitude direction is "W" the value has to be multiplied by -1. Another fact that has to be taken into account is, that each position data from the jackrabbit is of the structure "GPSPosition". The degrees are an integer value and the minutes are a float value. If the minutes are ≤ 9, dynamic C is not able to display the leading zero and appends the second digit directly onto the integer degree. A longitude of "7209.3600,W" (ddmm.mmmm) for example is displayed as "729.3600".

The sample test for Figure B.1was taken on March 22nd on lake mascoma. Two different loops were performed, to compare the track from the first to the second run. The first run is indicated with "_a" and the second with "_b". The distance two the first waypoint varies and

depends on the starting point. The distances between the other waypoints and the bearings are given in Table 8.2.

	distance	bearing
wp1,wp2	586 m	124.6°
wp2,wp3	642 m	210.0°
wp3,wp4	522 m	309.6°

Table 8.2: *Distances and bearings for the waypoints "lake mascoma bridge".*

The distances between the basing points is calculated by the distance between two waypoints. The desired distance between the basing points was about 100 m and the real distance is calculated by

$$\overline{bp(i),bp(i+1)} = \frac{\overline{wp(i),wp(i+1)}}{integer(\frac{\overline{wp(i),wp(i+1)}\ m}{100\ m})}$$

for waypoint1 and waypoint2 it is

$$\overline{bp(i),bp(i+1)} = \frac{586\ m}{integer(\frac{586\ m}{100\ m})} = \frac{586}{5} \cdot m = 117.2\ m$$

That guarantees the last basing point will coincide with the waypoint. In this test, I tried to generate each basing point from the current point while within the range to a waypoint or a basing point. One can see, that the basing points are perfectly positioned if the robot is on the track between the waypoints, but if he is off from the track, the next basing point will be off the track the same distance. So for the next test, I generated the basing points on the track between the two waypoints.

In this first test, the distances between the basing points were also not the same, because I calculated them from the current point within the range of the last basing point. I corrected that and the basing points are in the same distances.

The basing points outlined in the circles A, B, C, and D were generated unnecessarily. However the Cool Robot did not head for them, so they had no impact on the traveled path.

The two strange bends were caused by a wrong bearing calculation. The current bearing was calculated to 270° instead of 180°, so the robot made a left turn to get on its course again after recognizing to be off course again at the next navigation cycle. I corrected that.

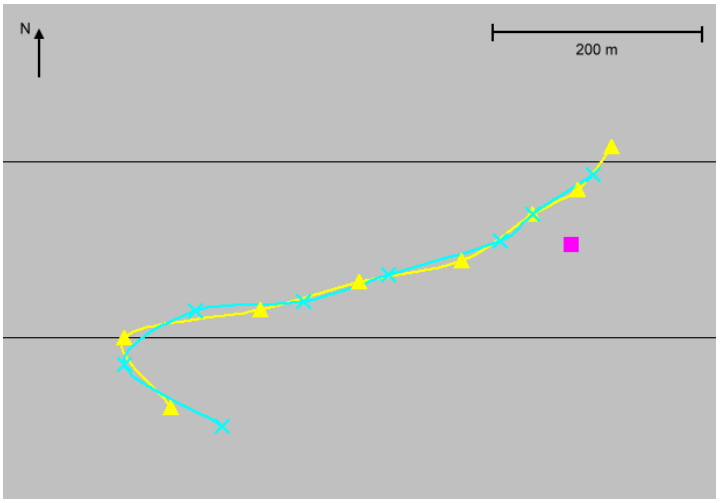


Figure 8.2: *Navigation routine at startup*

Figure 8.2 shows the startup for the second loop. Starting with the position determination at point 1, the robot drives straight ahead without a course correction. After the time between navigation cycles ("tm_nav") which was set to 15 seconds, the robot determines the current position[1] and calculates the first current bearing to 313°. At that point the bearing to the first basing point is 48°. A calculated off bearing of $48° + 360° - 313° = 95°$ leads to a right turn. In the drive mode "wp_follow_full" the motors on the right side are set to 90% to process a wide turn. After completing the course correction, current position[2] for the next navigation cycle is taken. Then the robot drives straight forward again at full speed for the next 15 seconds and determines current position[1] and the current bearing for the last 15 seconds. After completing the second course correction the off bearing for the next navigation cycle is at -25°. Due to the demanding terrain, the robot could not drive straight ahead. So the next course correction is 23°. After four course corrections, the off bearing is within a $\pm 10°$ range and the robot will not make any further major corrections.

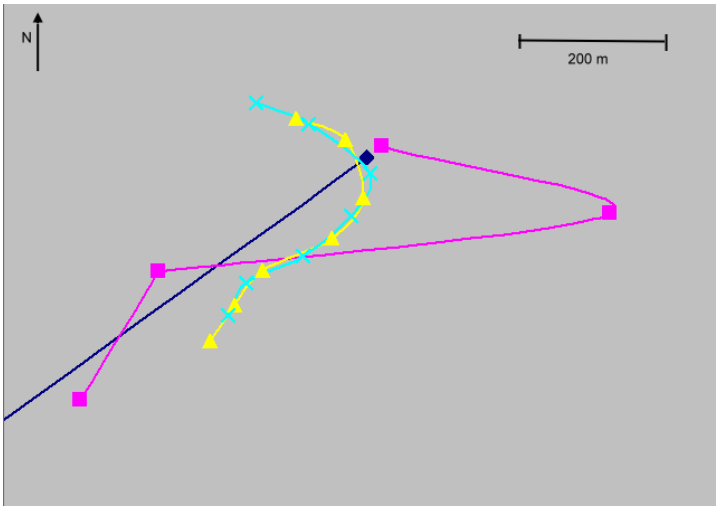


Figure 8.3: *Waypoint and basing point shifting sample*

Figure 8.3 shows an example waypoint shift from the test. The robot travels on the path following the basing point. As the last basing point is the waypoint, the algorithm recognizes that and heads for the waypoint instead of the basing point. As the range for generating the next basing point is larger than the range for activating the next waypoint, the algorithm generates one basing point more in the direction of the last waypoint, but does not head towards it.

The next test shown in Figure B.2 was made with some different parameters set as shown in Table 8.3.

wp_range	0.030
bp_range	0.045
tm_nav	15
dis_bp	0.5

Table 8.3: *Parameters for waypoint following at full speed 24 mar.*

The generated basing points coincide with the waypoints, because the calculation of the distance between basing points was set to 500 m and the distances between the waypoints were $\leq 1000 \cdot m$ (see Table 8.2). The error here was that the basing point was calculated from the current point which was within the range of the waypoint, but with the distance and the bearing between the waypoints so the basing point is calculated with a small offset which has been corrected. However there is again no effect on the navigation of the Cool Robot, because

it heads to the waypoint as it has a higher priority.

Comparing the two tests I had a close look at the bearings and the course corrections the Cool Robot had to perform.

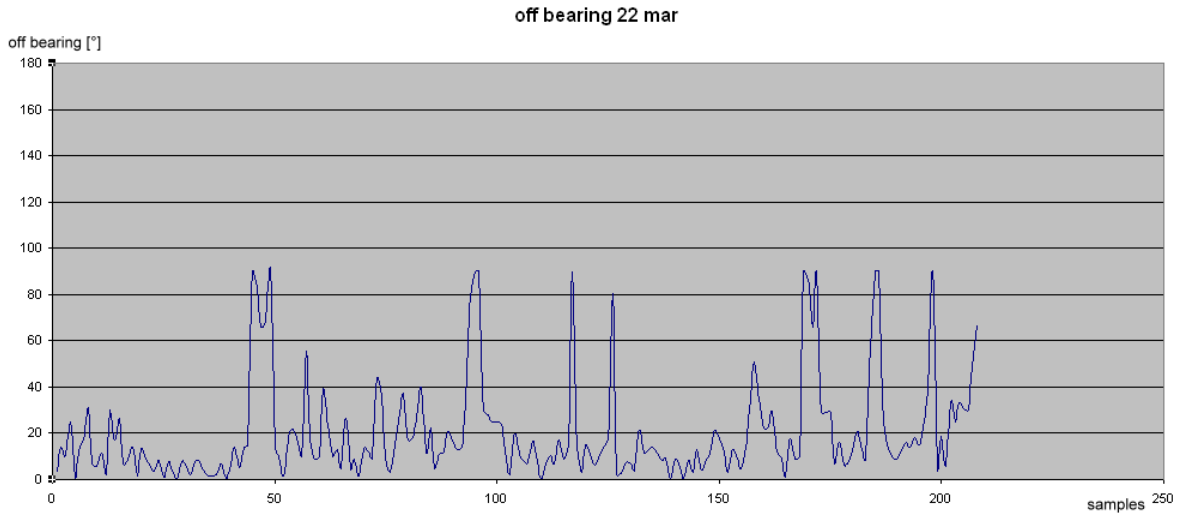


Figure 8.4: *Off bearing with basing points every 100 m*

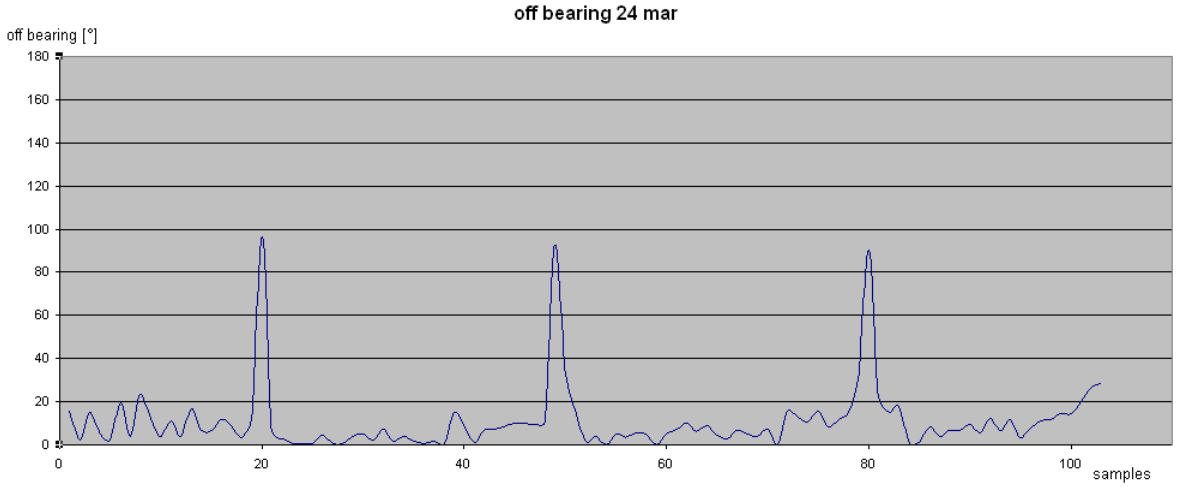


Figure 8.5: *Off bearing with basing points every 500 m*

In Figure 8.5 the three 90 degrees course changes after heading to a new waypoint are represented by the the peaks in the graph. It takes one course correction to get back on the new desired course and the off bearing stays within a range of $\pm$ 20 degrees. Figure 8.4 shows

the two loops, but the peaks from activating the next waypoint are not evident. It is obvious that the Cool Robot does make more course corrections if generating basing points every 100 m than every 500 m. It starts with a distance of about 100 m to a basing point where the off bearing is small, but the closer the robot gets to the basing point, the larger gets the off bearing, because the offset from track is greater compared to the distance to the basing point. By making more course corrections, the open loop course correction gets more imprecise and the traveled track is getting longer compared to the perfect shortest track between the waypoints.

Table 8.4 shows the calculated distances for the shortest track, the traveled path and the additional track traveled for making the course corrections.

	22 mar	24 mar
perfect track	4370 m	2194 m
traveled path	5131 m	2258 m
additional distance	760 m	64 m
percentage	17.4	2.9

Table 8.4: *Overview of distances.*

The perfect track is calculated between the starting point, waypoint1, waypoint2, waypoint3 and waypoint4. For the test on mar 22nd, the distance is larger because two loops were performed. The length of the traveled path was calculated with

$$X_{travel} = \sum_{i=0}^{wp4} currentdistance(i) + \sum_{i=0}^{wp4} turningdistance$$

whereas the turning distance is

$$X_{turn} = offbearing\,[^\circ] \cdot \frac{300}{1000} \cdot \left[\frac{sec}{^\circ}\right] \cdot 1.3 \left[\frac{m}{sec}\right]$$

I also calculated the false bearing in the first test out to have a stronger conclusion for the distance between the basing points. The test with a distance of 100 m between the basing points is not acceptable. A 17.4% deviation of the track compared to the perfect connection

between the waypoints is too much. The second case with a distance of 500 m or more between the basing points is within a good range. With a total track length of 500 km, the robot would travel 515 km which is equal to 103%. Further testing with varying parameters in Greenland has to evaluate the best navigation behavior.

The opposite is, that the offset from track is within a small range while heading for the basing points in a small distance, but as seen in Figure B.2 is the offset from track within the range of 20 m, controlled in the "navigate.lib".

8.2 Overall energy consumption on snow

The overall energy consumption on snow is basically the same as the energy consumption of the motors. The Jackrabbit and the peripheral parts draw only currents in the range of milli amperes. The following current data was taken on the golf course of Dartmouth College on february 18th which was a test with the **16 inch** tires on it! The sun was shining and the temperature was 34 F (1°C).

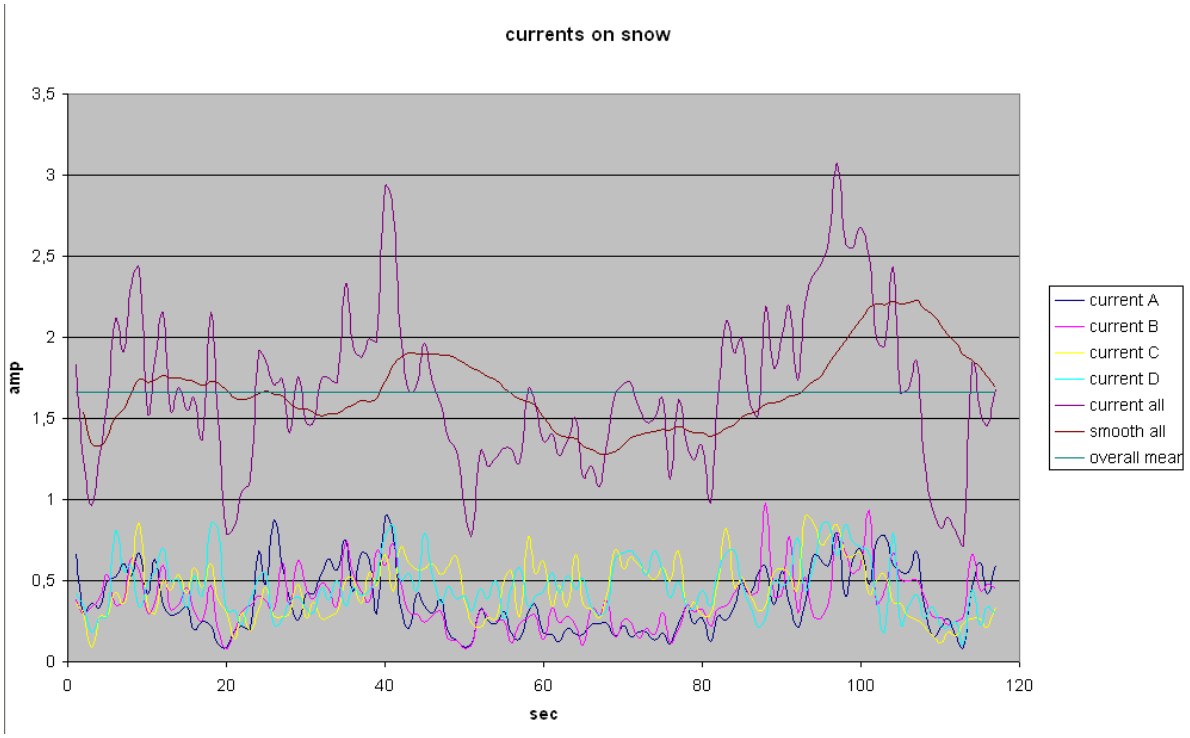


Figure 8.6: *Current draw data on snow*

The snow was already a few days old and was pretty firm. A lot of footprints had been made and the terrain was demanding. Viewing the different motor currents, one can tell very precisely what the current torque output for each wheel is. The overall mean current for all four wheels is 1.66 ampere. That would lead in an energy consumption of

$$E_{drive} \;=\; I_{all} \cdot U_{supply} \;=\; (1.66 \cdot 48)\ W \;=\; 79.68\ W \tag{8.1}$$

for the propulsion on flat terrain.

8.3 Rolling resistance

For the 16 inch tires, I took some current measurements for all wheels in different conditions. The total weight of the Cool Robot at that point was 82 lbs (38 kg). The temperature for the hard surface data was 25 F (-4°C) and the temperature for the high centered data was 70 F (21°C). The different values for the test data used to calculate the rolling resistance are outlined below.

Current mean value while high centered on a box: $I_{air} \;=\; 1.151 \cdot amp$

Current mean value on hard surface (pavement): $I_{roll} \;=\; 1.278 \cdot amp$

Torque constant for the motor ($\pm 10\%$: $K_T \;=\; 0.095 \cdot \frac{N \cdot m}{amp}$

radius of the 16 inch tires: $r \;=\; 7.5 \cdot inch \;=\; 0.1905 \cdot m$

transmission ratio (efficiency included): $tr \;=\; 100 \cdot 90\% \;=\; 0.9$

The surface rolling resistance then is calculated as

$$F_R \;=\; \frac{T \cdot tr}{r} \;=\; \frac{(I_{roll} - I_{air}) \cdot K_T \cdot tr}{r}$$

$$F_R = \frac{(1.278 - 1.151) \cdot amp \cdot 0.095 \cdot \frac{N \cdot m}{amp} \cdot 90}{0.1905 \cdot m} = 5.83\ N \tag{8.2}$$

The internal rolling resistance is

$$F_I = \frac{T_I \cdot tr}{r} = \frac{I_{air} \cdot K_T \cdot tr}{r} = \frac{1.151 \cdot amp \cdot 0.095 \cdot \frac{N \cdot m}{amp} \cdot 90}{0.1905 \cdot m} = 51.66\ N \tag{8.3}$$

Finally, the total rolling resistance is calculated as the sum of the internal rolling resistance and the surface rolling resistance. With a total weight of 82 lbs it is

$$F_{roll} = R_R + F_I = 5.83\ N + 51.66\ N = 57.49\ N \tag{8.4}$$

Guido and Gunnar measured a no-load current for a single motor of 0.272 A, which accounts for 1.088 ampere of the high centered current [4]. With the 1.151 ampere I measured on the box the bearing losses are calculated as

$$L_{bearing}\,[\%] = \frac{(I_{air} - I_{no\ load})}{I_{air}} \cdot 100\% = 5.47\ \% \tag{8.5}$$

of the internal resistance which is great.

8.4 Radio Interface and Communication

To sum up to the overall performance of the actual radio communication system: it is running well. In all different variants of the CoolRobots main program the radio connection is one major part and it is performing absolutely trouble-free, especially using the new ICOM 4088 radio. When running the system with the older, cheaper Cobra radios we encountered some

problems with the reliability of the system. Major issues were bad connections within the microphone and speaker jacks of the Cobra radios, as well as a low transmission quality and therefore a fairly short range of operation. Especially when the batteries of the radios were low problems occurred, because the radios did not stop to broadcast, and even though the push-to-talk was released by the radio modems they went on broadcasting. This effect jammed the radio connection and data could not be sent any more. The first tests on Mascoma Lake showed that the software for the communication system itself is running, but communication itself was fairly unstable due to the weak radio connection. The maximum range of operation only was approximately 300 meters in a really flat environment without any obstacles and on a clear day.

When switching to the new radios these problems disappeared and we were able to run the robot easily in manual drive mode as well as in waypoint following at full speed. In the first place we were a little bit concerned about the large amount of navigation data in combination with the low bandwidth (1200bit/s) of the radio link. But this worked out just fine, since the navigation algorithm takes about 30 seconds for each cycle, there is enough time to transmit even the big set navigation data. Sending one set of the navigation data takes all in all approximately 3 to 4 seconds. When running in manual drive mode most of the time there is not a really significant delay between sending a command from the Hyperterminal window until it is executed by the robot. In most cases this is not perceptible, only when trying to send a command while the robot is sending back its actual motor speeds or when sending two commands back-to-back it may take up to 3 seconds until the command is executed, because the first transmission blocks the channel for a certain time and only after this data exchange is finished the next packet of data can be transmitted. Therefore it is more effective to send one longer drive string rather then sending character by character. In order to find out what the maximum range of operation is like, we started the robot navigating to a waypoint 3km down the lake and watched the incoming navigation data until the connection was lost and no more data was received. Taking the last GPS position received from the robot and the GPS position of the car (see Figure 8.7), where the robot started, we calculated a distance of slightly above 1200 meters. Nearly four times the range achieved with the Cobra radios.

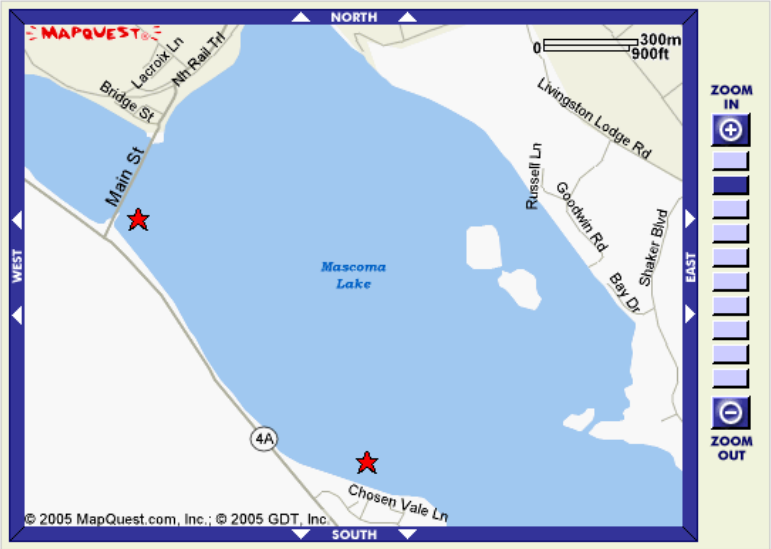


Figure 8.7: *Screen shot of "mapquest.com" showing the starting point and the point the last transmission was received before losing connection*

We were running several tests with the navigation algorithm on Mascoma Lake always getting all navigation data send back from the robot and never encountered a problem with the communication system. In the first tests we were driving behind the robot within a range of 200m to 300m to be sure no data is lost or the connection is interrupted. In the latest tests on a fairly cloudy day the robot was doing a rectangle shaped route with round about 600m to each side (see figure B.2) and the car with the receiving modem remained on the corner the robot started instead of driving relatively near to the robot. Thus the maximum distance was around 850m between robot and car and absolutely no problems occurred. I was watching the radio and modem all the time, but not even one packet was sent twice. So the software, as well as the hardware are performing consistently.

For further use it might be good idea to supply the radio on the robot by +5V of the internal housekeeping instead of batteries and maybe try to supply the radio modem and radio used by 12VDC from the cars cigarette lighter, as far as a car is available, just to eliminate the battery power problem. Although it is still performing without any problems the wiring between radios and modems should be rebuild at some point because the cable is still the one built for test purposes in the very beginning and its simply not the nicest and most reliable design. I think especially the capacitor-resistor circuitry for the push-to-talk (PTT) and transmit (TX)

signal should be moved out of the housing of plug. Furthermore there are certainly modification and changes possible for the software, especially in the case of a data and status request, since both are just implemented as an example of what can be done, but there is no real use for the control of the robot.

Appendix A

Functions and library overview

backwards_tilt	drive.lib
clearStr	radiocomm_e.lib
DispStr	drive.lib
faster_forwards	drive.lib
forward_full	drive.lib
forward_partial	drive.lib
getgps	gps.lib
high_centered	drive.lib
manual_drive	drive.lib
navigate	navigate.lib
processModemStr	radiocomm_e.lib
ReadAD	analogin.lib
read_sensors	analogin.lib
SendToDAC	drive.lib
sensor_high_centered	analogin.lib
sensor_range	analogin.lib
slower_forwards	drive.lib
SPI_Binit	SPI_B.lib
SPI_BRead	SPI_B.lib
SPI_BWrite	SPI_B.lib

SPI_BWrRd	SPI_B.lib
stop	drive.lib
str2wayp	radiocomm_e.lib
SwapBytes	drive.lib
termStr	radiocomm_e.lib
turn_full	navigate.lib
turn_left	drive.lib
turn_partial	navigate.lib
turn_right	drive.lib
UpdateMotorOutput	drive.lib
wp_follow_full	drive.lib
wp_follow_partial	drive.lib

A.1 Overview of parameters and variables

angle(main_prog):

Constant integer to set the turning difference for manual drive mode in percent. The two wheels on one side slows down for $\frac{angle}{2}$ and the other accelerates for $\frac{angle}{2}$ (default = 20).

bp_range(navigate.lib):

A float to set the radius for the circle around a basing point. Once within that range, the next basing point will be generated and the robot will change its heading. The range is the value in km (default = 0.045).

dis_bp(main_prog):

A float to roughly set the distance between two basing points. The distance between two waypoints will be divided by that value. The return value is rounded off to an integer and is the number of basing points on the track between the two waypoints. If the value is 0.5, the distance between two basing points could be 468 m or 512 m for example. This calculation makes sure the last basing point is the waypoint (default = 1.0).

drive_mode:

An integer that holds number of the actual drive mode and sets the drive mode entered when CoolRobot is started. In "mainprogV0.34" it is set to 5 at startup which equals manual drive mode. Accepted values are 1,2,3 and 5.

EINBUFSIZE:

Sets the size of serial port E's input buffer. The value must be $2^n - 1$ and is defaulted to 511bytes.

EOUTBUFSIZE:

Sets the size of serial port E's output buffer. The value must be $2^n - 1$ and is defaulted to 511bytes.

FS_USE_PROGRAM_FLASH:

Defined on beginning of the main program. This parameter for the file system determines how

much kilobyte of program flash memory are set aside for the file system. It is set to 16 at the moment but it is not essential if the second flash memory is used, because when using the second flash for the file system no program flash is needed.

GPS_inv_limit(main_prog):
Integer that sets the number of cycles to retry for a valid GPS string before returning to manual drive mode an stop. For the algorithm performing one GPS-data reading every second, it is also the time in seconds to retry for a valid data input (default = 30).

LOG_FILE_NAME:
Sets the file name of the logfile. The value must be an unsigned integer 1 to 255. It is set to $1 + LX\_2\_USE$ which equal 2, since the logic extend (LX) we are using number 1 (second flash) by default.

LX_2_USE:
Sets the logic extend (LX) to be used for the file system. It is set to 1 by the function "get_flash_ls()".

max_output(drive.lib):
Constant integer to set the maximum output varriation (default = 1220). The top speed for the Cool Robot is reached with an output voltage of 3 volts. The corresponding integer value to be sent out on serial port D is $zero\_output + max\_output = 2048 + 1220 = 3268$.

motor_speed_increment(main_prog):
Constant integer to set the difference in accelerating or slowing down for manual drive mode in percent (default = 10).

MY_LS_SIZE:
Defined on beginning of the main program. This parameter set the logical sector size of the file system as $log(base2)$ of the desired size. It affects the efficiency of the file system is set to 9 which equals 1024byte, the value that achieves maximum efficiency.

scale_motor(analogin.lib):
A float to convert the 12 bit output value to motor current. Channel 0, 1, 2 and 3 are converted

to motor current A, B, C and D. The input range is 5 volts and 1 V output voltage = 2A motor current (default = $5/4096.0 \cdot 2$).

scale_tilt(analogin.lib):
A float to convert the 12 bit output value to tilt roll and pitch. Channel 8 is roll and channel 9 is pitch. The input range is 5 volts and 1V = 1g. The tilt angle is the asin from the output voltage (default = $5/4096.0$)

scale_velocity(analogin.lib):
A float to convert the 12 bit output value to motor velocity. Channel 4, 5, 6 and 7 are converted to motor velocities A, B, C and D. The input range is 5 volts and 1V output voltge = 120Hz Hall frequency (default = $\frac{5 \cdot 120 \cdot 60}{4096.0 \cdot 2}$)

tilt_lim(analogin.lib):
An integer value for the maximum roll and pitch angle in degrees at which the robot should be interrupted and stopped (default = 45°).

tm_hc(main_prog):
An integer that defines the time the function "sensor_high_centered" waits until it switches the drive mode to "high_centered". The value is the time in seconds (default = 10 sec).

tm_nav(main_prog):
An integer that defines the time between current point[2] and current point[1] for each navigation cycle in the drive mode "wp_follow_full" in seconds. The time for the course corrections will be added! (default = 30).

tm_nav_low(main_prog):
An integer that defines the time between current point[2] and current point[1] for each navigation cycle in drive mode "wp_follow_partial" if the power does not allow waypoint following at full speed in seconds. The time for course corrections will be added! (default = 50). The time is automatically calculated with the value of "tm_nav".

tm_nav_wp(drive.lib):
An integer that defines the time between current point[2] and current point[1] for each navi-

gation cycle once within a range of 100 m to the last active waypoint in seconds. Defined to achieve a higher precision on reaching one exact point (default = 10)

turn_lim(navigate.lib):
An integer that limits the maximum turning angle for one navigation cycle in degrees. Makes the open loop course correction possible and is used to adjust the shifts in heading caused by sastrugi fields (default = 90).

wp_range(navigate.lib):
A float to set the radius for the circle around a waypoint. Once within that range the next waypoint is activated and the Cool Robot will continue navigating. The range is the value in km (default = 0.030).

zero_output(drive.lib):
Constant integer to set the zero output value of the DAC‘s. Zero volts output correspond with no revolutions of the motors (default = 2048).

Appendix B

GPS position and waypoint following test data

Table B.1 shows the data string sent back from the Cool Robot on march 24. For the abbreviations in the table see Table 5.14.

aw	4337,8985	N	-7209,3244	bp	4338,0999	N	-7209,12186												
aw	4338,1	N	-7209,12																
cp1	4337,9045	N	-7209,3139	cp2	4337,8985	N	-7209,3244	dw	0,444	bw	35,6	dbp	0,443	bbp	35,4	cd	0,017	cb	51,2
cp1	4337,9144	N	-7209,3019	cp2	4337,9078	N	-7209,3096	dw	0,421	bw	35,3	dbp	0,419	bbp	35,1	cd	0,016	cb	37,5
cp1	4337,9211	N	-7209,2925	cp2	4337,9144	N	-7209,3019	dw	0,403	bw	34,7	dbp	0,401	bbp	34,4	cd	0,019	cb	49,6
cp1	4337,9331	N	-7209,2842	cp2	4337,9252	N	-7209,2892	dw	0,378	bw	35,3	dbp	0,376	bbp	35,0	cd	0,018	cb	30,1
cp1	4337,9425	N	-7209,2738	cp2	4337,9353	N	-7209,2821	dw	0,356	bw	35,2	dbp	0,355	bbp	34,9	cd	0,018	cb	37,3
cp1	4337,9486	N	-7209,2632	cp2	4337,9425	N	-7209,2738	dw	0,339	bw	34,2	dbp	0,338	bbp	33,9	cd	0,018	cb	53,3
cp1	4337,9596	N	-7209,2506	cp2	4337,9521	N	-7209,2587	dw	0,313	bw	34,1	dbp	0,312	bbp	33,7	cd	0,017	cb	30,0
cp1	4337,9664	N	-7209,2373	cp2	4337,9613	N	-7209,248	dw	0,293	bw	32,4	dbp	0,291	bbp	32,0	cd	0,017	cb	55,4
cp1	4337,9762	N	-7209,2239	cp2	4337,9695	N	-7209,2327	dw	0,267	bw	31,1	dbp	0,266	bbp	30,7	cd	0,018	cb	43,1
cp1	4337,9888	N	-7209,2123	cp2	4337,9801	N	-7209,2204	dw	0,240	bw	31,0	dbp	0,239	bbp	30,5	cd	0,019	cb	34,6
cp1	4337,9965	N	-7209,2033	cp2	4337,9888	N	-7209,2123	dw	0,221	bw	30,1	dbp	0,220	bbp	29,6	cd	0,020	cb	41,0
cp1	4338,0112	N	-7209,1921	cp2	4338,0002	N	-7209,2001	dw	0,191	bw	30,4	dbp	0,189	bbp	29,8	cd	0,023	cb	25,8
cp1	4338,0198	N	-7209,1811	cp2	4338,0133	N	-7209,1899	dw	0,169	bw	28,7	dbp	0,167	bbp	28,1	cd	0,017	cb	44,9
cp1	4338,032	N	-7209,1733	cp2	4338,0235	N	-7209,1776	dw	0,143	bw	29,3	dbp	0,142	bbp	28,5	cd	0,018	cb	21,6
cp1	4338,0417	N	-7209,1638	cp2	4338,0344	N	-7209,1714	dw	0,123	bw	28,6	dbp	0,122	bbp	27,7	cd	0,016	cb	34,3
cp1	4338,0512	N	-7209,1541	cp2	4338,0437	N	-7209,1618	dw	0,100	bw	26,7	dbp	0,099	bbp	25,5	cd	0,018	cb	37,3
cp1	4338,0605	N	-7209,1457	cp2	4338,0533	N	-7209,1522	dw	0,080	bw	25,0	dbp	0,079	bbp	23,6	cd	0,016	cb	32,7
cp1	4338,0727	N	-7209,1375	cp2	4338,0627	N	-7209,144	dw	0,055	bw	24,7	dbp	0,054	bbp	22,6	cd	0,020	cb	25,8
cp1	4338,0814	N	-7209,1302	cp2	4338,0727	N	-7209,1375	dw	0,036	bw	21,5	dbp	0,035	bbp	18,2	cd	0,019	cb	30,7
cp1	4338,0928	N	-7209,1208	cp2	4338,0838	N	-7209,1283	dw	0,013	bw	0,0	dbp	0,576	bbp	37,4	cd	0,019	cb	30,6
aw	4337,92	N	-7208,76	bp	4337,91267	N	-7208,76205												
cp1	4338,0913	N	-7209,0889	cp2	4338,0957	N	-7209,1012	dw	0,542	bw	125,8	dbp	0,548	bbp	127,0	cd	0,018	cb	120,6
cp1	4338,0835	N	-7209,0736	cp2	4338,0899	N	-7209,0858	dw	0,517	bw	125,9	dbp	0,523	bbp	127,2	cd	0,020	cb	124,6
cp1	4338,077	N	-7209,0612	cp2	4338,0835	N	-7209,0736	dw	0,497	bw	125,9	dbp	0,502	bbp	127,2	cd	0,020	cb	126,4
cp1	4338,0715	N	-7209,0505	cp2	4338,077	N	-7209,0612	dw	0,479	bw	125,8	dbp	0,485	bbp	127,2	cd	0,018	cb	126,7
cp1	4338,0659	N	-7209,0401	cp2	4338,0715	N	-7209,0505	dw	0,462	bw	125,8	dbp	0,468	bbp	127,2	cd	0,016	cb	126,8
cp1	4338,0605	N	-7209,0296	cp2	4338,0659	N	-7209,0401	dw	0,444	bw	125,9	dbp	0,450	bbp	127,4	cd	0,018	cb	122,7
cp1	4338,0554	N	-7209,0199	cp2	4338,0605	N	-7209,0296	dw	0,429	bw	125,9	dbp	0,435	bbp	127,4	cd	0,015	cb	127,0
cp1	4338,0498	N	-7209,0099	cp2	4338,0554	N	-7209,0199	dw	0,413	bw	125,9	dbp	0,419	bbp	127,5	cd	0,016	cb	126,8
cp1	4338,0443	N	-7209,0011	cp2	4338,0498	N	-7209,0099	dw	0,397	bw	125,6	dbp	0,402	bbp	127,3	cd	0,016	cb	131,3
cp1	4338,0374	N	-7208,9875	cp2	4338,0428	N	-7208,9984	dw	0,373	bw	125,7	dbp	0,379	bbp	127,5	cd	0,018	cb	122,7
cp1	4338,0323	N	-7208,978	cp2	4338,0374	N	-7208,9875	dw	0,358	bw	125,5	dbp	0,364	bbp	127,4	cd	0,014	cb	129,6
cp1	4338,0262	N	-7208,9625	cp2	4338,0309	N	-7208,9748	dw	0,335	bw	126,0	dbp	0,341	bbp	128,0	cd	0,018	cb	120,6
cp1	4338,019	N	-7208,949	cp2	4338,0248	N	-7208,9595	dw	0,312	bw	126,0	dbp	0,318	bbp	128,1	cd	0,018	cb	126,7
cp1	4338,0134	N	-7208,939	cp2	4338,019	N	-7208,949	dw	0,294	bw	126,1	dbp	0,300	bbp	128,3	cd	0,017	cb	124,6
cp1	4338,0077	N	-7208,9282	cp2	4338,0134	N	-7208,939	dw	0,277	bw	126,1	dbp	0,283	bbp	128,4	cd	0,018	cb	126,6
cp1	4338,0024	N	-7208,9182	cp2	4338,0077	N	-7208,9282	dw	0,261	bw	125,9	dbp	0,267	bbp	128,4	cd	0,016	cb	129,2
cp1	4337,9969	N	-7208,9079	cp2	4338,0024	N	-7208,9182	dw	0,243	bw	125,8	dbp	0,249	bbp	128,5	cd	0,018	cb	126,6
cp1	4337,9909	N	-7208,8985	cp2	4337,9969	N	-7208,9079	dw	0,227	bw	125,6	dbp	0,233	bbp	128,5	cd	0,017	cb	128,8
cp1	4337,984	N	-7208,8908	cp2	4337,9909	N	-7208,8985	dw	0,211	bw	124,3	dbp	0,217	bbp	127,5	cd	0,016	cb	142,6
cp1	4337,9762	N	-7208,8743	cp2	4337,9811	N	-7208,8855	dw	0,185	bw	124,5	dbp	0,191	bbp	128,0	cd	0,017	cb	118,5
cp1	4337,9691	N	-7208,8615	cp2	4337,9747	N	-7208,8713	dw	0,164	bw	124,0	dbp	0,170	bbp	128,0	cd	0,016	cb	129,2
cp1	4337,9631	N	-7208,8471	cp2	4337,9677	N	-7208,8585	dw	0,141	bw	124,4	dbp	0,147	bbp	129,0	cd	0,017	cb	122,5
cp1	4337,9584	N	-7208,8368	cp2	4337,9631	N	-7208,8471	dw	0,125	bw	124,6	dbp	0,131	bbp	129,8	cd	0,016	cb	122,3
cp1	4337,9529	N	-7208,8258	cp2	4337,9584	N	-7208,8368	dw	0,107	bw	125,0	dbp	0,113	bbp	131,0	cd	0,018	cb	122,7
cp1	4337,9474	N	-7208,8139	cp2	4337,9529	N	-7208,8258	dw	0,089	bw	125,5	dbp	0,095	bbp	132,6	cd	0,018	cb	122,7

cp1	4337,9421	N	-7208,8035	cp2	4337,9474	N	-7208,8139	dw	0,070	bw	125,7	dbp	0,077	bbp	134,5	cd	0,019	cb	124,7
cp1	4337,9367	N	-7208,7935	cp2	4337,9421	N	-7208,8035	dw	0,054	bw	125,3	dbp	0,061	bbp	136,5	cd	0,016	cb	126,8
cp1	4337,9308	N	-7208,7832	cp2	4337,9367	N	-7208,7935	dw	0,037	bw	123,7	dbp	0,044	bbp	139,5	cd	0,017	cb	128,9
cp1	4337,9244	N	-7208,7695	cp2	4337,9291	N	-7208,7801	dw	0,015	bw	127,0	dbp	0,604	bbp	125,9	cd	0,017	cb	120,3
aw	4337,62	N	-7209	bp	4337,62474	N	-7209,00925												
cp1	4337,9021	N	-7208,7605	cp2	4337,9119	N	-7208,7605	dw	0,612	bw	211,5	dbp	0,610	bbp	213,0	cd	0,017	cb	180,0
cp1	4337,884	N	-7208,7673	cp2	4337,895	N	-7208,7619	dw	0,578	bw	212,6	dbp	0,577	bbp	214,1	cd	0,021	cb	197,8
cp1	4337,8718	N	-7208,7773	cp2	4337,8799	N	-7208,77	dw	0,553	bw	212,5	dbp	0,552	bbp	214,1	cd	0,017	cb	215,9
cp1	4337,8637	N	-7208,7843	cp2	4337,8718	N	-7208,7773	dw	0,535	bw	212,6	dbp	0,534	bbp	214,2	cd	0,018	cb	210,1
cp1	4337,8558	N	-7208,7912	cp2	4337,8637	N	-7208,7843	dw	0,518	bw	212,5	dbp	0,517	bbp	214,2	cd	0,017	cb	214,4
cp1	4337,8484	N	-7208,798	cp2	4337,8558	N	-7208,7912	dw	0,502	bw	212,6	dbp	0,501	bbp	214,3	cd	0,016	cb	209,3
cp1	4337,8407	N	-7208,8042	cp2	4337,8484	N	-7208,798	dw	0,485	bw	212,7	dbp	0,484	bbp	214,5	cd	0,017	cb	211,4
cp1	4337,8324	N	-7208,8108	cp2	4337,8407	N	-7208,8042	dw	0,467	bw	212,8	dbp	0,466	bbp	214,7	cd	0,018	cb	208,9
cp1	4337,8243	N	-7208,8173	cp2	4337,8324	N	-7208,8108	dw	0,450	bw	212,9	dbp	0,449	bbp	214,9	cd	0,018	cb	210,1
cp1	4337,815	N	-7208,825	cp2	4337,8243	N	-7208,8173	dw	0,430	bw	212,9	dbp	0,429	bbp	214,9	cd	0,019	cb	214,6
cp1	4337,8072	N	-7208,8317	cp2	4337,815	N	-7208,825	dw	0,413	bw	213,0	dbp	0,412	bbp	215,1	cd	0,018	cb	210,1
cp1	4337,7998	N	-7208,8379	cp2	4337,8072	N	-7208,8317	dw	0,396	bw	213,2	dbp	0,396	bbp	215,4	cd	0,016	cb	208,0
cp1	4337,7915	N	-7208,8488	cp2	4337,7978	N	-7208,8402	dw	0,375	bw	212,5	dbp	0,375	bbp	214,8	cd	0,017	cb	224,9
cp1	4337,7826	N	-7208,86	cp2	4337,7894	N	-7208,8514	dw	0,354	bw	211,9	dbp	0,353	bbp	214,4	cd	0,017	cb	220,5
cp1	4337,7717	N	-7208,8679	cp2	4337,7795	N	-7208,8632	dw	0,331	bw	212,2	dbp	0,330	bbp	214,8	cd	0,015	cb	205,8
cp1	4337,7619	N	-7208,8766	cp2	4337,7695	N	-7208,8697	dw	0,311	bw	212,2	dbp	0,310	bbp	215,0	cd	0,015	cb	210,8
cp1	4337,7531	N	-7208,8849	cp2	4337,7619	N	-7208,8766	dw	0,290	bw	212,2	dbp	0,289	bbp	215,2	cd	0,021	cb	212,2
cp1	4337,7458	N	-7208,8929	cp2	4337,7531	N	-7208,8849	dw	0,272	bw	211,6	dbp	0,271	bbp	214,7	cd	0,018	cb	221,5
cp1	4337,7355	N	-7208,9012	cp2	4337,7437	N	-7208,8947	dw	0,251	bw	211,6	dbp	0,250	bbp	215,1	cd	0,018	cb	210,1
cp1	4337,7277	N	-7208,9075	cp2	4337,7355	N	-7208,9012	dw	0,234	bw	211,6	dbp	0,233	bbp	215,3	cd	0,017	cb	211,4
cp1	4337,7189	N	-7208,9149	cp2	4337,7277	N	-7208,9075	dw	0,216	bw	211,9	dbp	0,215	bbp	215,9	cd	0,018	cb	208,9
cp1	4337,7109	N	-7208,922	cp2	4337,7189	N	-7208,9149	dw	0,197	bw	211,5	dbp	0,196	bbp	215,9	cd	0,019	cb	215,9
cp1	4337,6999	N	-7208,928	cp2	4337,7086	N	-7208,9235	dw	0,176	bw	213,1	dbp	0,176	bbp	218,0	cd	0,017	cb	202,5
cp1	4337,6893	N	-7208,9355	cp2	4337,6974	N	-7208,9295	dw	0,155	bw	214,1	dbp	0,155	bbp	219,7	cd	0,017	cb	206,9
cp1	4337,6789	N	-7208,9447	cp2	4337,6871	N	-7208,9374	dw	0,132	bw	213,9	dbp	0,132	bbp	220,5	cd	0,018	cb	210,0
cp1	4337,671	N	-7208,9509	cp2	4337,6789	N	-7208,9447	dw	0,115	bw	215,0	dbp	0,115	bbp	222,5	cd	0,017	cb	206,8
cp1	4337,6611	N	-7208,9609	cp2	4337,6689	N	-7208,9526	dw	0,092	bw	214,8	dbp	0,093	bbp	224,1	cd	0,017	cb	215,9
cp1	4337,6534	N	-7208,9678	cp2	4337,6611	N	-7208,9609	dw	0,075	bw	214,9	dbp	0,076	bbp	226,4	cd	0,017	cb	214,4
cp1	4337,6461	N	-7208,9742	cp2	4337,6534	N	-7208,9678	dw	0,059	bw	215,0	dbp	0,061	bbp	229,4	cd	0,016	cb	214,3
cp1	4337,6387	N	-7208,9803	cp2	4337,6461	N	-7208,9742	dw	0,042	bw	218,3	dbp	0,045	bbp	237,7	cd	0,017	cb	206,9
cp1	4337,6301	N	-7208,9907	cp2	4337,6368	N	-7208,9824	dw	0,022	bw	213,6	dbp	0,026	bbp	249,4	cd	0,016	cb	222,1
aw	4337,8002	N	-7209,3001	bp	4337,81013	N	-7209,29306												
cp1	4337,6291	N	-7209,0215	cp2	4337,6264	N	-7209,0102	dw	0,489	bw	310,2	dbp	0,494	bbp	312,6	cd	0,015	cb	290,4
cp1	4337,6353	N	-7209,0396	cp2	4337,6305	N	-7209,0277	dw	0,464	bw	311,1	dbp	0,469	bbp	313,6	cd	0,017	cb	298,5
cp1	4337,641	N	-7209,0548	cp2	4337,6367	N	-7209,0435	dw	0,441	bw	312,0	dbp	0,446	bbp	314,5	cd	0,018	cb	296,9
cp1	4337,6515	N	-7209,0699	cp2	4337,6449	N	-7209,0607	dw	0,414	bw	311,7	dbp	0,420	bbp	314,5	cd	0,017	cb	315,2
cp1	4337,6574	N	-7209,0791	cp2	4337,6515	N	-7209,0699	dw	0,398	bw	311,7	dbp	0,403	bbp	314,5	cd	0,017	cb	313,3
cp1	4337,6632	N	-7209,0891	cp2	4337,6574	N	-7209,0791	dw	0,380	bw	311,9	dbp	0,385	bbp	314,9	cd	0,018	cb	306,7
cp1	4337,671	N	-7209,1005	cp2	4337,6649	N	-7209,0918	dw	0,359	bw	311,8	dbp	0,364	bbp	315,0	cd	0,016	cb	311,3
cp1	4337,6766	N	-7209,1098	cp2	4337,671	N	-7209,1005	dw	0,342	bw	312,0	dbp	0,348	bbp	315,3	cd	0,017	cb	308,8
cp1	4337,6825	N	-7209,12	cp2	4337,6766	N	-7209,1098	dw	0,325	bw	312,1	dbp	0,331	bbp	315,6	cd	0,017	cb	308,8
cp1	4337,6878	N	-7209,1297	cp2	4337,6825	N	-7209,12	dw	0,309	bw	312,4	dbp	0,314	bbp	316,1	cd	0,016	cb	306,8
cp1	4337,6953	N	-7209,1424	cp2	4337,6895	N	-7209,1323	dw	0,287	bw	312,5	dbp	0,293	bbp	316,4	cd	0,017	cb	310,8
cp1	4337,7009	N	-7209,1518	cp2	4337,6953	N	-7209,1424	dw	0,271	bw	313,0	dbp	0,277	bbp	317,1	cd	0,016	cb	304,6
cp1	4337,7084	N	-7209,1646	cp2	4337,7025	N	-7209,1544	dw	0,249	bw	313,0	dbp	0,255	bbp	317,5	cd	0,017	cb	310,8
cp1	4337,7141	N	-7209,1743	cp2	4337,7084	N	-7209,1646	dw	0,233	bw	313,4	dbp	0,239	bbp	318,2	cd	0,016	cb	306,8
cp1	4337,7222	N	-7209,1859	cp2	4337,716	N	-7209,1767	dw	0,211	bw	313,3	dbp	0,217	bbp	318,6	cd	0,017	cb	315,1
cp1	4337,7277	N	-7209,1948	cp2	4337,7222	N	-7209,1859	dw	0,195	bw	313,5	dbp	0,201	bbp	319,2	cd	0,016	cb	311,3
cp1	4337,7338	N	-7209,2049	cp2	4337,7277	N	-7209,1948	dw	0,178	bw	313,9	dbp	0,185	bbp	320,1	cd	0,017	cb	308,9
cp1	4337,7408	N	-7209,2165	cp2	4337,7354	N	-7209,2073	dw	0,158	bw	314,2	dbp	0,164	bbp	321,2	cd	0,016	cb	309,2
cp1	4337,7486	N	-7209,2293	cp2	4337,7423	N	-7209,2192	dw	0,135	bw	315,0	dbp	0,142	bbp	323,1	cd	0,018	cb	308,6
cp1	4337,7562	N	-7209,2413	cp2	4337,7502	N	-7209,2317	dw	0,114	bw	316,0	dbp	0,122	bbp	325,4	cd	0,017	cb	310,8
cp1	4337,7639	N	-7209,2537	cp2	4337,7579	N	-7209,244	dw	0,092	bw	317,2	dbp	0,100	bbp	328,4	cd	0,018	cb	308,6
cp1	4337,7732	N	-7209,2688	cp2	4337,7657	N	-7209,2561	dw	0,066	bw	319,9	dbp	0,076	bbp	334,5	cd	0,021	cb	308,0
cp1	4337,781	N	-7209,2805	cp2	4337,7748	N	-7209,2711	dw	0,045	bw	322,4	dbp	0,057	bbp	342,0	cd	0,017	cb	313,3

Table B.2 shows the test data from the waypoint following test on march 22nd.

	4337,9849	N	-7209,261															
aw	4338,1	N	-7209,12	bp	4338,0235	N	-7209,217											
cp1	4337,9849	N	-7209,261	cp2	4337,9779	N	-7209,268	dw	0,284	bw	41,5	dbp	0,093	bbp	39,7	cd	0,017	cb	35,9
cp1	4337,9922	N	-7209,255	cp2	4337,9849	N	-7209,261	dw	0,269	bw	42,3	dbp	0,077	bbp	42,2	cd	0,016	cb	28,0
cp1	4338,0011	N	-7209,241	cp2	4337,9952	N	-7209,251	dw	0,244	bw	41,6	dbp	0,052	bbp	38,8	cd	0,017	cb	49,2
cp1	4338,0085	N	-7209,229	cp2	4338,0028	N	-7209,239	dw	0,224	bw	40,7	dbp	0,033	bbp	30,4	cd	0,016	cb	55,4
cp1	4338,0182	N	-7209,218	cp2	4338,0118	N	-7209,225	dw	0,199	bw	40,9	dbp	0,088	bbp	38,5	cd	0,016	cb	39,1
cp1	4338,0239	N	-7209,209	cp2	4338,0182	N	-7209,218	dw	0,183	bw	40,2	dbp	0,072	bbp	36,2	cd	0,016	cb	48,7
cp1	4338,0321	N	-7209,197	cp2	4338,026	N	-7209,206	dw	0,161	bw	39,2	dbp	0,051	bbp	31,3	cd	0,017	cb	49,2
cp1	4338,0447	N	-7209,191	cp2	4338,0367	N	-7209,194	dw	0,140	bw	43,0	dbp	0,028	bbp	44,0	cd	0,015	cb	12,8
cp1	4338,0574	N	-7209,181	cp2	4338,05	N	-7209,188	dw	0,113	bw	45,8	dbp	0,086	bbp	41,5	cd	0,016	cb	34,3
cp1	4338,0652	N	-7209,17	cp2	4338,0592	N	-7209,179	dw	0,093	bw	45,7	dbp	0,066	bbp	40,1	cd	0,015	cb	46,0
cp1	4338,0748	N	-7209,162	cp2	4338,0672	N	-7209,168	dw	0,073	bw	50,0	dbp	0,046	bbp	44,3	cd	0,016	cb	32,8
cp1	4338,0827	N	-7209,152	cp2	4338,0769	N	-7209,16	dw	0,054	bw	52,7	dbp	0,026	bbp	45,7	cd	0,015	cb	48,1
cp1	4338,0882	N	-7209,136	cp2	4338,0845	N	-7209,147	dw	0,030	bw	43,5	dbp	0,090	bbp	32,2	cd	0,016	cb	62,0
cp1	4338,097	N	-7209,123	cp2	4338,0912	N	-7209,131	dw	0,006	bw	32,3	dbp	0,067	bbp	27,1	cd	0,016	cb	44,0
aw	4337,92	N	-7208,76	bp	4338,0614	N	-7209,051												
cp1	4338,0959	N	-7209,094	cp2	4338,0992	N	-7209,105	dw	0,552	bw	126,1	dbp	0,085	bbp	138,2	cd	0,016	cb	111,6
cp1	4338,0862	N	-7209,079	cp2	4338,0925	N	-7209,088	dw	0,525	bw	125,9	dbp	0,059	bbp	142,0	cd	0,017	cb	135,1
cp1	4338,0779	N	-7209,068	cp2	4338,0844	N	-7209,076	dw	0,505	bw	125,4	dbp	0,037	bbp	144,1	cd	0,016	cb	136,0
cp1	4338,0703	N	-7209,058	cp2	4338,0762	N	-7209,066	dw	0,485	bw	124,9	dbp	0,018	bbp	151,1	cd	0,014	cb	137,1
cp1	4338,0636	N	-7209,044	cp2	4338,0684	N	-7209,054	dw	0,463	bw	125,0	dbp	0,092	bbp	126,2	cd	0,016	cb	124,6
cp1	4338,0599	N	-7209,034	cp2	4338,0636	N	-7209,044	dw	0,449	bw	125,4	dbp	0,078	bbp	128,3	cd	0,014	cb	114,7
cp1	4338,0537	N	-7209,019	cp2	4338,0584	N	-7209,03	dw	0,426	bw	125,6	dbp	0,055	bbp	131,1	cd	0,017	cb	122,5
cp1	4338,0453	N	-7209,005	cp2	4338,0511	N	-7209,015	dw	0,402	bw	125,4	dbp	0,031	bbp	132,7	cd	0,016	cb	126,8
cp1	4338,04	N	-7208,996	cp2	4338,0453	N	-7209,005	dw	0,385	bw	125,2	dbp	0,098	bbp	125,0	cd	0,017	cb	128,9
cp1	4338,0356	N	-7208,985	cp2	4338,04	N	-7208,996	dw	0,369	bw	125,5	dbp	0,082	bbp	126,4	cd	0,016	cb	118,0
cp1	4338,029	N	-7208,973	cp2	4338,0341	N	-7208,982	dw	0,348	bw	125,4	dbp	0,061	bbp	125,8	cd	0,016	cb	126,8
cp1	4338,0249	N	-7208,962	cp2	4338,029	N	-7208,973	dw	0,333	bw	125,6	dbp	0,046	bbp	127,8	cd	0,015	cb	119,9
cp1	4338,0177	N	-7208,949	cp2	4338,0235	N	-7208,959	dw	0,310	bw	125,7	dbp	0,023	bbp	130,8	cd	0,018	cb	126,6
cp1	4338,0125	N	-7208,938	cp2	4338,0177	N	-7208,949	dw	0,293	bw	125,7	dbp	0,099	bbp	125,0	cd	0,017	cb	124,6
cp1	4338,0079	N	-7208,927	cp2	4338,0125	N	-7208,938	dw	0,276	bw	126,2	dbp	0,082	bbp	126,4	cd	0,017	cb	118,5
cp1	4338,0008	N	-7208,916	cp2	4338,0066	N	-7208,924	dw	0,257	bw	125,9	dbp	0,063	bbp	125,2	cd	0,015	cb	131,9
cp1	4337,9937	N	-7208,902	cp2	4337,9984	N	-7208,912	dw	0,234	bw	125,9	dbp	0,040	bbp	124,6	cd	0,016	cb	122,4
cp1	4337,9892	N	-7208,891	cp2	4337,9937	N	-7208,902	dw	0,216	bw	126,3	dbp	0,022	bbp	127,9	cd	0,018	cb	120,6
cp1	4337,9825	N	-7208,877	cp2	4337,9875	N	-7208,887	dw	0,194	bw	127,0	dbp	0,092	bbp	127,0	cd	0,017	cb	118,5
cp1	4337,9755	N	-7208,864	cp2	4337,981	N	-7208,874	dw	0,173	bw	126,9	dbp	0,071	bbp	126,7	cd	0,017	cb	122,5
cp1	4337,9687	N	-7208,852	cp2	4337,9739	N	-7208,861	dw	0,152	bw	126,8	dbp	0,050	bbp	126,1	cd	0,016	cb	124,6
cp1	4337,964	N	-7208,842	cp2	4337,9687	N	-7208,852	dw	0,137	bw	126,7	dbp	0,035	bbp	125,7	cd	0,015	cb	127,0
cp1	4337,9591	N	-7208,832	cp2	4337,964	N	-7208,842	dw	0,119	bw	127,0	dbp	0,018	bbp	126,6	cd	0,017	cb	124,6
cp1	4337,9549	N	-7208,822	cp2	4337,9591	N	-7208,832	dw	0,104	bw	128,1	dbp	0,099	bbp	126,4	cd	0,015	cb	119,9
cp1	4337,9482	N	-7208,809	cp2	4337,9535	N	-7208,819	dw	0,084	bw	129,4	dbp	0,079	bbp	127,4	cd	0,016	cb	126,8
cp1	4337,9437	N	-7208,8	cp2	4337,9482	N	-7208,809	dw	0,068	bw	130,5	dbp	0,063	bbp	128,1	cd	0,016	cb	124,6
cp1	4337,9395	N	-7208,789	cp2	4337,9437	N	-7208,8	dw	0,053	bw	134,1	dbp	0,048	bbp	131,3	cd	0,015	cb	117,4
cp1	4337,9326	N	-7208,775	cp2	4337,9379	N	-7208,785	dw	0,031	bw	138,4	dbp	0,026	bbp	134,3	cd	0,016	cb	129,2
cp1	4337,9238	N	-7208,763	cp2	4337,9299	N	-7208,771	dw	0,008	bw	156,3	dbp	0,091	bbp	123,9	cd	0,016	cb	137,9
aw	4337,62	N	-7209	bp	4337,8738	N	-7208,804												
cp1	4337,9033	N	-7208,759	cp2	4337,9124	N	-7208,758	dw	0,615	bw	211,6	dbp	0,081	bbp	227,9	cd	0,017	cb	270,0
cp1	4337,8905	N	-7208,748	cp2	4337,8969	N	-7208,755	dw	0,603	bw	214,0	dbp	0,082	bbp	247,7	cd	0,016	cb	140,8
cp1	4337,8678	N	-7208,748	cp2	4337,8763	N	-7208,745	dw	0,569	bw	216,3	dbp	0,075	bbp	278,1	cd	0,017	cb	195,4
cp1	4337,8539	N	-7208,77	cp2	4337,8576	N	-7208,76	dw	0,530	bw	215,4	dbp	0,058	bbp	309,6	cd	0,017	cb	243,7
cp1	4337,8541	N	-7208,796	cp2	4337,8527	N	-7208,784	dw	0,511	bw	212,3	dbp	0,039	bbp	343,6	cd	0,015	cb	275,6
cp1	4337,8671	N	-7208,815	cp2	4337,8599	N	-7208,809	dw	0,518	bw	208,4	dbp	0,020	bbp	50,0	cd	0,015	cb	324,1
cp1	4337,8603	N	-7208,839	cp2	4337,8681	N	-7208,832	dw	0,493	bw	205,8	dbp	0,083	bbp	196,8	cd	0,018	cb	210,1
cp1	4337,8492	N	-7208,843	cp2	4337,8576	N	-7208,841	dw	0,473	bw	206,4	dbp	0,062	bbp	198,4	cd	0,016	cb	188,1
cp1	4337,8372	N	-7208,848	cp2	4337,8456	N	-7208,844	dw	0,449	bw	206,8	dbp	0,038	bbp	198,3	cd	0,016	cb	199,9
cp1	4337,8285	N	-7208,85	cp2	4337,8372	N	-7208,848	dw	0,434	bw	207,5	dbp	0,023	bbp	205,8	cd	0,016	cb	188,1
cp1	4337,8164	N	-7208,853	cp2	4337,8247	N	-7208,851	dw	0,413	bw	208,4	dbp	0,085	bbp	214,7	cd	0,016	cb	192,6
cp1	4337,804	N	-7208,86	cp2	4337,8126	N	-7208,855	dw	0,389	bw	208,8	dbp	0,062	bbp	219,6	cd	0,015	cb	200,9
cp1	4337,7941	N	-7208,873	cp2	4337,7998	N	-7208,865	dw	0,364	bw	207,8	dbp	0,036	bbp	217,3	cd	0,015	cb	228,1
cp1	4337,7828	N	-7208,878	cp2	4337,7909	N	-7208,875	dw	0,342	bw	208,5	dbp	0,017	bbp	243,7	cd	0,015	cb	188,5
cp1	4337,771	N	-7208,883	cp2	4337,7785	N	-7208,88	dw	0,320	bw	209,3	dbp	0,086	bbp	215,0	cd	0,015	cb	197,1
cp1	4337,7596	N	-7208,895	cp2	4337,7663	N	-7208,887	dw	0,294	bw	208,5	dbp	0,060	bbp	213,3	cd	0,016	cb	222,2
cp1	4337,7505	N	-7208,9	cp2	4337,7578	N	-7208,896	dw	0,276	bw	208,7	dbp	0,042	bbp	217,1	cd	0,014	cb	207,1
cp1	4337,74	N	-7208,905	cp2	4337,7484	N	-7208,902	dw	0,256	bw	209,8	dbp	0,024	bbp	235,4	cd	0,016	cb	196,2
cp1	4337,7301	N	-7208,909	cp2	4337,7373	N	-7208,907	dw	0,238	bw	211,1	dbp	0,089	bbp	213,6	cd	0,013	cb	189,8
cp1	4337,7175	N	-7208,916	cp2	4337,7253	N	-7208,911	dw	0,212	bw	211,8	dbp	0,064	bbp	217,1	cd	0,017	cb	206,8
cp1	4337,7065	N	-7208,924	cp2	4337,7141	N	-7208,918	dw	0,189	bw	212,2	dbp	0,041	bbp	222,1	cd	0,016	cb	209,4
cp1	4337,6979	N	-7208,935	cp2	4337,7041	N	-7208,927	dw	0,169	bw	210,9	dbp	0,020	bbp	221,0	cd	0,015	cb	225,9
cp1	4337,6856	N	-7208,94	cp2	4337,694	N	-7208,938	dw	0,145	bw	213,6	dbp	0,083	bbp	213,7	cd	0,017	cb	187,5
cp1	4337,6717	N	-7208,95	cp2	4337,6793	N	-7208,944	dw	0,117	bw	214,3	dbp	0,055	bbp	215,4	cd	0,015	cb	210,8
cp1	4337,6619	N	-7208,959	cp2	4337,6696	N	-7208,952	dw	0,095	bw	215,1	dbp	0,034	bbp	218,1	cd	0,016	cb	209,4
cp1	4337,652	N	-7208,967	cp2	4337,6594	N	-7208,961	dw	0,074	bw	216,6	dbp	0,086	bbp	209,9	cd	0,017	cb	211,4
cp1	4337,643	N	-7208,976	cp2	4337,6499	N	-7208,969	dw	0,052	bw	215,9	dbp	0,065	bbp	207,2	cd	0,017	cb	220,4
cp1	4337,6329	N	-7208,981	cp2	4337,6411	N	-7208,977	dw	0,034	bw	227,0	dbp	0,046	bbp	212,0	cd	0,016	cb	200,0
cp1	4337,622	N	-7208,992	cp2	4337,6281	N	-7208,985	dw	0,011	bw	254,6	dbp	0,021	bbp	208,5	cd	0,014	cb	217,6
aw	4337,8	N	-7209,3	bp	4337,6572	N	-7209,053												
cp1	4337,6195	N	-7209,022	cp2	4337,6179	N	-7209,01	dw	0,501	bw	311,8	dbp	0,082	bbp	328,5	cd	0,015	cb	284,9
cp1	4337,6277	N	-7209,04	cp2	4337,6228	N	-7209,031	dw	0,472	bw	312,6	dbp	0,057	bbp	343,3	cd	0,015	cb	307,0
cp1	4337,642	N	-7209,051	cp2	4337,634	N	-7209,046	dw	0,444	bw	311,2	dbp	0,028	bbp	353,5	cd	0,016	cb	343,9
cp1	4337,6513	N	-7209,065	cp2	4337,6462	N	-7209,056	dw	0,418	bw	311,2	dbp	0,080	bbp	307,8	cd	0,016	cb	304,6
cp1	4337,6567	N	-7209,073	cp2	4337,6513	N	-7209,065	dw	0,405	bw	310,9	dbp	0,067	bbp	305,2	cd	0,014	cb	320,4
cp1	4337,6619	N	-7209,091	cp2	4337,6594	N	-7209,079	dw	0,379	bw	312,3	dbp	0,041	bbp	314,2	cd	0,017	cb	285,4
cp1	4337,6682	N	-7209,108	cp2	4337,6643	N	-7209,098	dw	0,355	bw	313,4	dbp	0,019	bbp	339,3	cd	0,016	cb	302,3
cp1	4337,6733	N	-7209,123	cp2	4337,6696	N	-7209,112	dw	0,334	bw	314,6	dbp	0,084	bbp	312,8	cd	0,016	cb	295,5
cp1	4337,6797	N	-7209,139	cp2	4337,6756	N	-7209,128	dw	0,312	bw	315,8	dbp	0,061	bbp	318,3	cd	0,015	cb	299,9
cp1	4337,6863	N	-7209,153	cp2	4337,682	N	-7209,144	dw	0,289	bw	317,0	dbp	0,039	bbp	328,0	cd	0,014	cb	302,1
cp1	4337,6966	N	-7209,167	cp2	4337,6901	N	-7209,159	dw	0,262	bw	317,3	dbp	0,014	bbp	356,0	cd	0,016	cb	316,0

cp1	4337,702	N	-7209,181	cp2	4337,6984	N	-7209,171	dw	0,242	bw	318,5	dbp	0,085	bbp	310,1	cd	0,016	cb	298,0
cp1	4337,7072	N	-7209,195	cp2	4337,7033	N	-7209,184	dw	0,223	bw	320,7	dbp	0,065	bbp	315,1	cd	0,016	cb	293,0
cp1	4337,7158	N	-7209,209	cp2	4337,7101	N	-7209,201	dw	0,198	bw	322,2	dbp	0,040	bbp	319,0	cd	0,015	cb	314,0
cp1	4337,7247	N	-7209,221	cp2	4337,7186	N	-7209,213	dw	0,175	bw	323,1	dbp	0,017	bbp	324,1	cd	0,017	cb	313,2
cp1	4337,7299	N	-7209,235	cp2	4337,7264	N	-7209,225	dw	0,156	bw	325,9	dbp	0,085	bbp	310,1	cd	0,016	cb	298,0
cp1	4337,7342	N	-7209,25	cp2	4337,7311	N	-7209,239	dw	0,140	bw	330,9	dbp	0,065	bbp	316,3	cd	0,016	cb	295,6
cp1	4337,7418	N	-7209,266	cp2	4337,7367	N	-7209,256	dw	0,118	bw	336,5	dbp	0,041	bbp	324,1	cd	0,015	cb	307,0
cp1	4337,7506	N	-7209,277	cp2	4337,7449	N	-7209,269	dw	0,097	bw	340,9	dbp	0,019	bbp	332,2	cd	0,015	cb	319,0
cp1	4337,7608	N	-7209,289	cp2	4337,7539	N	-7209,281	dw	0,075	bw	347,5	dbp	0,083	bbp	305,5	cd	0,017	cb	319,6
cp1	4337,7726	N	-7209,299	cp2	4337,7655	N	-7209,293	dw	0,051	bw	270,0	dbp	0,059	bbp	296,1	cd	0,017	cb	328,6
cp1	4337,7713	N	-7209,321	cp2	4337,7753	N	-7209,311	dw	0,062	bw	27,6	dbp	0,037	bbp	322,1	cd	0,017	cb	243,8
cp1	4337,7735	N	-7209,347	cp2	4337,7701	N	-7209,337	dw	0,080	bw	51,3	dbp	0,027	bbp	23,7	cd	0,015	cb	290,4
cp1	4337,7906	N	-7209,335	cp2	4337,7852	N	-7209,344	dw	0,049	bw	67,1	dbp	0,104	bbp	290,0	cd	0,015	cb	55,3
cp1	4337,7969	N	-7209,323	cp2	4337,792	N	-7209,332	dw	0,031	bw	77,5	dbp	0,114	bbp	281,9	cd	0,015	cb	55,4
aw	4337,8301	N	-7209,352	bp	4337,8761	N	-7209,283												
aw	4338,1	N	-7209,12	bp	4337,8761	N	-7209,283												
cp1	4337,8301	N	-7209,352	cp2	4337,8246	N	-7209,343	dw	0,586	bw	31,9	dbp	0,124	bbp	47,9	cd	0,017	cb	313,3
cp1	4337,8498	N	-7209,36	cp2	4337,8421	N	-7209,36	dw	0,563	bw	34,7	dbp	0,114	bbp	64,8	cd	0,014	cb	270,0
cp1	4337,8579	N	-7209,337	cp2	4337,8577	N	-7209,348	dw	0,533	bw	32,9	dbp	0,079	bbp	64,9	cd	0,015	cb	90,0
cp1	4337,866	N	-7209,32	cp2	4337,8603	N	-7209,329	dw	0,509	bw	31,7	dbp	0,053	bbp	69,8	cd	0,015	cb	46,0
cp1	4337,8719	N	-7209,302	cp2	4337,8678	N	-7209,315	dw	0,486	bw	30,0	dbp	0,026	bbp	74,9	cd	0,019	cb	66,6
cp1	4337,8853	N	-7209,29	cp2	4337,8774	N	-7209,295	dw	0,457	bw	29,7	dbp	0,087	bbp	24,4	cd	0,017	cb	26,8
cp1	4337,8923	N	-7209,282	cp2	4337,8853	N	-7209,29	dw	0,441	bw	29,3	dbp	0,071	bbp	20,7	cd	0,017	cb	40,4
cp1	4337,9044	N	-7209,276	cp2	4337,8964	N	-7209,28	dw	0,418	bw	30,1	dbp	0,048	bbp	23,0	cd	0,016	cb	12,3
cp1	4337,915	N	-7209,269	cp2	4337,9078	N	-7209,274	dw	0,396	bw	30,3	dbp	0,026	bbp	19,9	cd	0,016	cb	28,1
cp1	4337,9227	N	-7209,263	cp2	4337,915	N	-7209,269	dw	0,379	bw	30,2	dbp	0,099	bbp	25,5	cd	0,016	cb	32,8
cp1	4337,9333	N	-7209,26	cp2	4337,9249	N	-7209,262	dw	0,360	bw	31,1	dbp	0,080	bbp	28,8	cd	0,016	cb	12,2
cp1	4337,9444	N	-7209,253	cp2	4337,9369	N	-7209,258	dw	0,338	bw	31,6	dbp	0,057	bbp	31,0	cd	0,014	cb	23,1
cp1	4337,9546	N	-7209,245	cp2	4337,9464	N	-7209,252	dw	0,316	bw	31,8	dbp	0,036	bbp	31,6	cd	0,017	cb	31,4
cp1	4337,962	N	-7209,239	cp2	4337,9546	N	-7209,245	dw	0,300	bw	32,0	dbp	0,019	bbp	34,5	cd	0,016	cb	28,0
cp1	4337,9706	N	-7209,234	cp2	4337,962	N	-7209,239	dw	0,284	bw	32,7	dbp	0,099	bbp	29,2	cd	0,017	cb	18,9
cp1	4337,9801	N	-7209,228	cp2	4337,9727	N	-7209,233	dw	0,265	bw	33,1	dbp	0,080	bbp	29,5	cd	0,014	cb	23,0
cp1	4337,9881	N	-7209,218	cp2	4337,9819	N	-7209,226	dw	0,244	bw	32,3	dbp	0,059	bbp	25,1	cd	0,016	cb	42,1
cp1	4338,0006	N	-7209,212	cp2	4337,9917	N	-7209,216	dw	0,220	bw	33,6	dbp	0,035	bbp	27,9	cd	0,017	cb	19,0
cp1	4338,011	N	-7209,207	cp2	4338,003	N	-7209,211	dw	0,201	bw	35,0	dbp	0,016	bbp	39,2	cd	0,016	cb	24,7
cp1	4338,0221	N	-7209,207	cp2	4338,011	N	-7209,207	dw	0,185	bw	38,9	dbp	0,099	bbp	33,6	cd	0,020	cb	356,9
cp1	4338,0338	N	-7209,196	cp2	4338,029	N	-7209,205	dw	0,159	bw	39,9	dbp	0,073	bbp	33,8	cd	0,015	cb	48,0
cp1	4338,045	N	-7209,186	cp2	4338,0369	N	-7209,192	dw	0,134	bw	40,8	dbp	0,048	bbp	33,2	cd	0,017	cb	30,0
cp1	4338,053	N	-7209,181	cp2	4338,045	N	-7209,186	dw	0,118	bw	43,2	dbp	0,032	bbp	38,3	cd	0,017	cb	23,4
cp1	4338,0622	N	-7209,177	cp2	4338,053	N	-7209,181	dw	0,102	bw	47,6	dbp	0,097	bbp	28,2	cd	0,018	cb	17,4
cp1	4338,0724	N	-7209,172	cp2	4338,0644	N	-7209,176	dw	0,085	bw	53,2	dbp	0,078	bbp	29,6	cd	0,017	cb	23,4
cp1	4338,0817	N	-7209,167	cp2	4338,0746	N	-7209,171	dw	0,070	bw	61,5	dbp	0,059	bbp	32,4	cd	0,015	cb	22,1
cp1	4338,0917	N	-7209,161	cp2	4338,0837	N	-7209,166	dw	0,057	bw	74,5	dbp	0,041	bbp	38,4	cd	0,016	cb	24,6
cp1	4338,1007	N	-7209,155	cp2	4338,0944	N	-7209,159	dw	0,046	bw	91,9	dbp	0,022	bbp	47,4	cd	0,013	cb	30,1
cp1	4338,1056	N	-7209,131	cp2	4338,1062	N	-7209,142	dw	0,018	bw	126,6	dbp	0,096	bbp	12,4	cd	0,015	cb	92,8
aw	4337,92	N	-7208,76	bp	4338,0701	N	-7209,06												
cp1	4338,099	N	-7209,113	cp2	4338,1041	N	-7209,124	dw	0,577	bw	125,1	dbp	0,090	bbp	126,6	cd	0,016	cb	124,6
cp1	4338,0934	N	-7209,105	cp2	4338,099	N	-7209,113	dw	0,561	bw	125,0	dbp	0,073	bbp	126,1	cd	0,017	cb	128,9
cp1	4338,0878	N	-7209,095	cp2	4338,0934	N	-7209,105	dw	0,546	bw	124,8	dbp	0,059	bbp	124,7	cd	0,015	cb	131,9
cp1	4338,0826	N	-7209,082	cp2	4338,0866	N	-7209,092	dw	0,525	bw	124,9	dbp	0,038	bbp	126,5	cd	0,015	cb	119,9
cp1	4338,0758	N	-7209,07	cp2	4338,0812	N	-7209,079	dw	0,504	bw	124,9	dbp	0,017	bbp	128,9	cd	0,017	cb	124,7
cp1	4338,069	N	-7209,063	cp2	4338,0758	N	-7209,07	dw	0,489	bw	124,4	dbp	0,101	bbp	121,1	cd	0,016	cb	142,6
cp1	4338,0608	N	-7209,05	cp2	4338,0659	N	-7209,059	dw	0,467	bw	124,0	dbp	0,079	bbp	117,9	cd	0,016	cb	129,3
cp1	4338,0565	N	-7209,035	cp2	4338,0597	N	-7209,047	dw	0,446	bw	124,6	dbp	0,058	bbp	120,4	cd	0,017	cb	107,9
cp1	4338,0527	N	-7209,02	cp2	4338,0554	N	-7209,031	dw	0,425	bw	125,2	dbp	0,038	bbp	125,6	cd	0,017	cb	111,5
cp1	4338,0454	N	-7209,004	cp2	4338,0503	N	-7209,014	dw	0,400	bw	125,5	dbp	0,013	bbp	136,1	cd	0,016	cb	124,6
cp1	4338,0414	N	-7208,994	cp2	4338,0454	N	-7209,004	dw	0,384	bw	125,9	dbp	0,100	bbp	126,1	cd	0,016	cb	118,0
cp1	4338,0356	N	-7208,98	cp2	4338,0401	N	-7208,991	dw	0,364	bw	126,1	dbp	0,080	bbp	127,3	cd	0,016	cb	118,0
cp1	4338,0288	N	-7208,969	cp2	4338,0341	N	-7208,978	dw	0,344	bw	125,9	dbp	0,060	bbp	126,4	cd	0,016	cb	126,8
cp1	4338,0246	N	-7208,959	cp2	4338,0288	N	-7208,969	dw	0,329	bw	126,2	dbp	0,045	bbp	128,6	cd	0,015	cb	119,9
cp1	4338,018	N	-7208,947	cp2	4338,0233	N	-7208,957	dw	0,309	bw	126,3	dbp	0,025	bbp	131,8	cd	0,016	cb	124,6
cp1	4338,0133	N	-7208,937	cp2	4338,018	N	-7208,947	dw	0,293	bw	126,4	dbp	0,099	bbp	125,0	cd	0,016	cb	124,6
cp1	4338,0093	N	-7208,926	cp2	4338,0133	N	-7208,937	dw	0,277	bw	126,8	dbp	0,083	bbp	126,4	cd	0,016	cb	118,0
cp1	4338,0033	N	-7208,914	cp2	4338,0082	N	-7208,923	dw	0,258	bw	126,9	dbp	0,064	bbp	126,3	cd	0,014	cb	129,6
cp1	4337,9974	N	-7208,907	cp2	4338,0033	N	-7208,914	dw	0,242	bw	126,3	dbp	0,048	bbp	123,2	cd	0,016	cb	135,9
cp1	4337,99	N	-7208,893	cp2	4337,9948	N	-7208,903	dw	0,220	bw	126,3	dbp	0,027	bbp	120,6	cd	0,016	cb	124,7
cp1	4337,9866	N	-7208,883	cp2	4337,99	N	-7208,893	dw	0,204	bw	126,9	dbp	0,099	bbp	126,4	cd	0,016	cb	118,0
cp1	4337,9815	N	-7208,869	cp2	4337,9855	N	-7208,88	dw	0,185	bw	128,1	dbp	0,081	bbp	129,1	cd	0,016	cb	118,0
cp1	4337,9767	N	-7208,856	cp2	4337,9804	N	-7208,866	dw	0,166	bw	129,8	dbp	0,061	bbp	134,1	cd	0,015	cb	113,0
cp1	4337,9686	N	-7208,84	cp2	4337,9736	N	-7208,85	dw	0,140	bw	130,5	dbp	0,036	bbp	139,8	cd	0,016	cb	122,3
cp1	4337,9599	N	-7208,827	cp2	4337,9658	N	-7208,835	dw	0,117	bw	129,6	dbp	0,012	bbp	148,2	cd	0,016	cb	136,1
cp1	4337,9529	N	-7208,812	cp2	4337,9575	N	-7208,823	dw	0,092	bw	131,6	dbp	0,090	bbp	125,4	cd	0,017	cb	122,5
cp1	4337,9493	N	-7208,802	cp2	4337,9529	N	-7208,812	dw	0,079	bw	134,7	dbp	0,076	bbp	127,5	cd	0,014	cb	114,7
cp1	4337,9434	N	-7208,789	cp2	4337,948	N	-7208,799	dw	0,058	bw	138,9	dbp	0,055	bbp	129,2	cd	0,015	cb	119,9
cp1	4337,9349	N	-7208,776	cp2	4337,9408	N	-7208,784	dw	0,035	bw	143,4	dbp	0,032	bbp	126,9	cd	0,016	cb	131,3
cp1	4337,9267	N	-7208,765	cp2	4337,9327	N	-7208,773	dw	0,014	bw	152,9	dbp	0,094	bbp	123,1	cd	0,014	cb	137,1
aw	4337,62	N	-7209	bp	4337,8765	N	-7208,806												
cp1	4337,9048	N	-7208,761	cp2	4337,9141	N	-7208,759	dw	0,616	bw	211,2	dbp	0,079	bbp	228,1	cd	0,016	cb	191,9
cp1	4337,8894	N	-7208,768	cp2	4337,8978	N	-7208,764	dw	0,587	bw	212,0	dbp	0,057	bbp	245,5	cd	0,017	cb	194,6
cp1	4337,8768	N	-7208,783	cp2	4337,8823	N	-7208,774	dw	0,556	bw	211,3	dbp	0,030	bbp	268,5	cd	0,016	cb	233,2
cp1	4337,8636	N	-7208,789	cp2	4337,8723	N	-7208,787	dw	0,532	bw	212,0	dbp	0,082	bbp	214,0	cd	0,016	cb	191,9
cp1	4337,85	N	-7208,795	cp2	4337,8595	N	-7208,791	dw	0,504	bw	212,7	dbp	0,056	bbp	221,8	cd	0,020	cb	199,1
cp1	4337,8373	N	-7208,803	cp2	4337,8452	N	-7208,798	dw	0,479	bw	213,3	dbp	0,033	bbp	236,4	cd	0,017	cb	206,9
cp1	4337,8291	N	-7208,807	cp2	4337,8373	N	-7208,803	dw	0,464	bw	213,7	dbp	0,092	bbp	212,5	cd	0,016	cb	199,9
cp1	4337,8186	N	-7208,813	cp2	4337,8255	N	-7208,809	dw	0,443	bw	214,1	dbp	0,071	bbp	214,8	cd	0,015	cb	205,7
cp1	4337,8081	N	-7208,823	cp2	4337,8151	N	-7208,816	dw	0,421	bw	214,2	dbp	0,049	bbp	215,4	cd	0,016	cb	214,3
cp1	4337,8006	N	-7208,828	cp2	4337,8081	N	-7208,823	dw	0,405	bw	214,6	dbp	0,033	bbp	221,2	cd	0,017	cb	203,4
cp1	4337,7918	N	-7208,836	cp2	4337,7982	N	-7208,83	dw	0,386	bw	214,6	dbp	0,089	bbp	208,7	cd	0,014	cb	217,7
cp1	4337,7804	N	-7208,839	cp2	4337,7882	N	-7208,837	dw	0,367	bw	216,2	dbp	0,069	bbp	215,9	cd	0,014	cb	270,0
cp1	4337,77	N	-7208,823	cp2	4337,7739	N	-7208,833	dw	0,364	bw	220,4	dbp	0,070	bbp	237,9	cd	0,014	cb	122,1

cp1	4337,7479	N	-7208,819	cp2	4337,7573	N	-7208,817	dw	0,338	bw	225,7	dbp	0,066	bbp	273,3	cd	0,018	cb	186,9
cp1	4337,7347	N	-7208,84	cp2	4337,7386	N	-7208,83	dw	0,301	bw	225,3	dbp	0,047	bbp	307,7	cd	0,016	cb	242,0
cp1	4337,7318	N	-7208,865	cp2	4337,7332	N	-7208,854	dw	0,275	bw	221,2	dbp	0,034	bbp	352,7	cd	0,014	cb	260,9
cp1	4337,7161	N	-7208,873	cp2	4337,7234	N	-7208,872	dw	0,246	bw	223,7	dbp	0,079	bbp	214,6	cd	0,014	cb	185,4
cp1	4337,7015	N	-7208,879	cp2	4337,7099	N	-7208,874	dw	0,222	bw	227,3	dbp	0,054	bbp	225,4	cd	0,016	cb	196,2
cp1	4337,6883	N	-7208,889	cp2	4337,6968	N	-7208,882	dw	0,196	bw	229,7	dbp	0,028	bbp	240,5	cd	0,017	cb	211,4
cp1	4337,6805	N	-7208,893	cp2	4337,6883	N	-7208,889	dw	0,181	bw	231,8	dbp	0,091	bbp	211,4	cd	0,016	cb	204,6
cp1	4337,6716	N	-7208,898	cp2	4337,6784	N	-7208,894	dw	0,167	bw	235,4	dbp	0,073	bbp	214,8	cd	0,014	cb	199,0
cp1	4337,6607	N	-7208,906	cp2	4337,6681	N	-7208,9	dw	0,146	bw	238,8	dbp	0,050	bbp	215,9	cd	0,016	cb	209,4
cp1	4337,6514	N	-7208,914	cp2	4337,6587	N	-7208,908	dw	0,128	bw	243,2	dbp	0,029	bbp	219,3	cd	0,016	cb	212,8
cp1	4337,6432	N	-7208,918	cp2	4337,6514	N	-7208,914	dw	0,117	bw	248,7	dbp	0,090	bbp	212,2	cd	0,016	cb	199,9
cp1	4337,6325	N	-7208,923	cp2	4337,6408	N	-7208,92	dw	0,106	bw	257,6	dbp	0,071	bbp	216,9	cd	0,016	cb	196,2
cp1	4337,62	N	-7208,932	cp2	4337,6276	N	-7208,927	dw	0,090	bw	270,0	dbp	0,045	bbp	221,0	cd	0,016	cb	208,1
cp1	4337,6109	N	-7208,941	cp2	4337,6177	N	-7208,934	dw	0,080	bw	282,6	dbp	0,024	bbp	226,5	cd	0,016	cb	217,4
cp1	4337,6031	N	-7208,964	cp2	4337,6064	N	-7208,954	dw	0,056	bw	303,4	dbp	0,082	bbp	195,5	cd	0,016	cb	250,9
cp1	4337,602	N	-7208,996	cp2	4337,6014	N	-7208,977	dw	0,034	bw	350,7	dbp	0,079	bbp	165,6	cd	0,025	cb	271,7
cp1	4337,6144	N	-7209,019	cp2	4337,6079	N	-7209,011	dw	0,028	bw	68,1	dbp	0,112	bbp	152,6	cd	0,016	cb	317,8
aw	4337,8	N	-7209,3	bp	4337,6504	N	-7209,08												
cp1	4337,6194	N	-7209,034	cp2	4337,616	N	-7209,022	dw	0,489	bw	313,3	dbp	0,085	bbp	313,5	cd	0,017	cb	287,9
cp1	4337,6256	N	-7209,048	cp2	4337,6216	N	-7209,04	dw	0,467	bw	313,9	dbp	0,062	bbp	318,0	cd	0,013	cb	304,7
cp1	4337,6324	N	-7209,059	cp2	4337,6274	N	-7209,051	dw	0,448	bw	313,9	dbp	0,044	bbp	319,5	cd	0,013	cb	310,1
cp1	4337,6414	N	-7209,07	cp2	4337,6353	N	-7209,062	dw	0,426	bw	313,7	dbp	0,022	bbp	322,9	cd	0,015	cb	314,0
cp1	4337,6477	N	-7209,084	cp2	4337,6434	N	-7209,074	dw	0,405	bw	314,3	dbp	0,085	bbp	310,5	cd	0,016	cb	298,0
cp1	4337,6529	N	-7209,098	cp2	4337,6491	N	-7209,088	dw	0,384	bw	315,1	dbp	0,064	bbp	314,2	cd	0,016	cb	298,0
cp1	4337,6612	N	-7209,114	cp2	4337,6557	N	-7209,104	dw	0,358	bw	315,9	dbp	0,038	bbp	320,8	cd	0,018	cb	306,6
cp1	4337,6708	N	-7209,129	cp2	4337,6645	N	-7209,12	dw	0,332	bw	316,1	dbp	0,013	bbp	335,8	cd	0,016	cb	317,8
cp1	4337,6762	N	-7209,143	cp2	4337,6724	N	-7209,132	dw	0,312	bw	317,3	dbp	0,086	bbp	312,2	cd	0,015	cb	297,4
cp1	4337,682	N	-7209,16	cp2	4337,6781	N	-7209,148	dw	0,289	bw	319,3	dbp	0,062	bbp	319,2	cd	0,017	cb	294,0
cp1	4337,6887	N	-7209,178	cp2	4337,6846	N	-7209,167	dw	0,264	bw	321,4	dbp	0,038	bbp	334,3	cd	0,017	cb	296,3
cp1	4337,6984	N	-7209,195	cp2	4337,693	N	-7209,186	dw	0,236	bw	322,9	dbp	0,018	bbp	18,1	cd	0,015	cb	311,9
cp1	4337,7043	N	-7209,203	cp2	4337,6984	N	-7209,195	dw	0,220	bw	323,7	dbp	0,089	bbp	308,2	cd	0,017	cb	313,3
cp1	4337,7089	N	-7209,216	cp2	4337,7054	N	-7209,205	dw	0,204	bw	326,1	dbp	0,072	bbp	311,6	cd	0,016	cb	293,0
cp1	4337,7173	N	-7209,229	cp2	4337,7114	N	-7209,22	dw	0,180	bw	328,1	dbp	0,047	bbp	311,5	cd	0,016	cb	317,9
cp1	4337,7212	N	-7209,243	cp2	4337,7185	N	-7209,232	dw	0,164	bw	332,2	dbp	0,029	bbp	325,0	cd	0,017	cb	291,5
cp1	4337,7261	N	-7209,259	cp2	4337,723	N	-7209,249	dw	0,149	bw	337,6	dbp	0,085	bbp	313,9	cd	0,014	cb	289,0
cp1	4337,7308	N	-7209,274	cp2	4337,7278	N	-7209,264	dw	0,133	bw	345,3	dbp	0,063	bbp	322,5	cd	0,016	cb	289,0
cp1	4337,7386	N	-7209,291	cp2	4337,7338	N	-7209,282	dw	0,115	bw	354,1	dbp	0,039	bbp	335,2	cd	0,016	cb	304,6
cp1	4337,7498	N	-7209,304	cp2	4337,7436	N	-7209,298	dw	0,094	bw	2,3	dbp	0,015	bbp	270,0	cd	0,014	cb	320,5
cp1	4337,7643	N	-7209,309	cp2	4337,7563	N	-7209,307	dw	0,068	bw	10,0	dbp	0,085	bbp	298,3	cd	0,015	cb	347,2
cp1	4337,7764	N	-7209,312	cp2	4337,7685	N	-7209,311	dw	0,047	bw	18,9	dbp	0,073	bbp	283,7	cd	0,014	cb	350,7

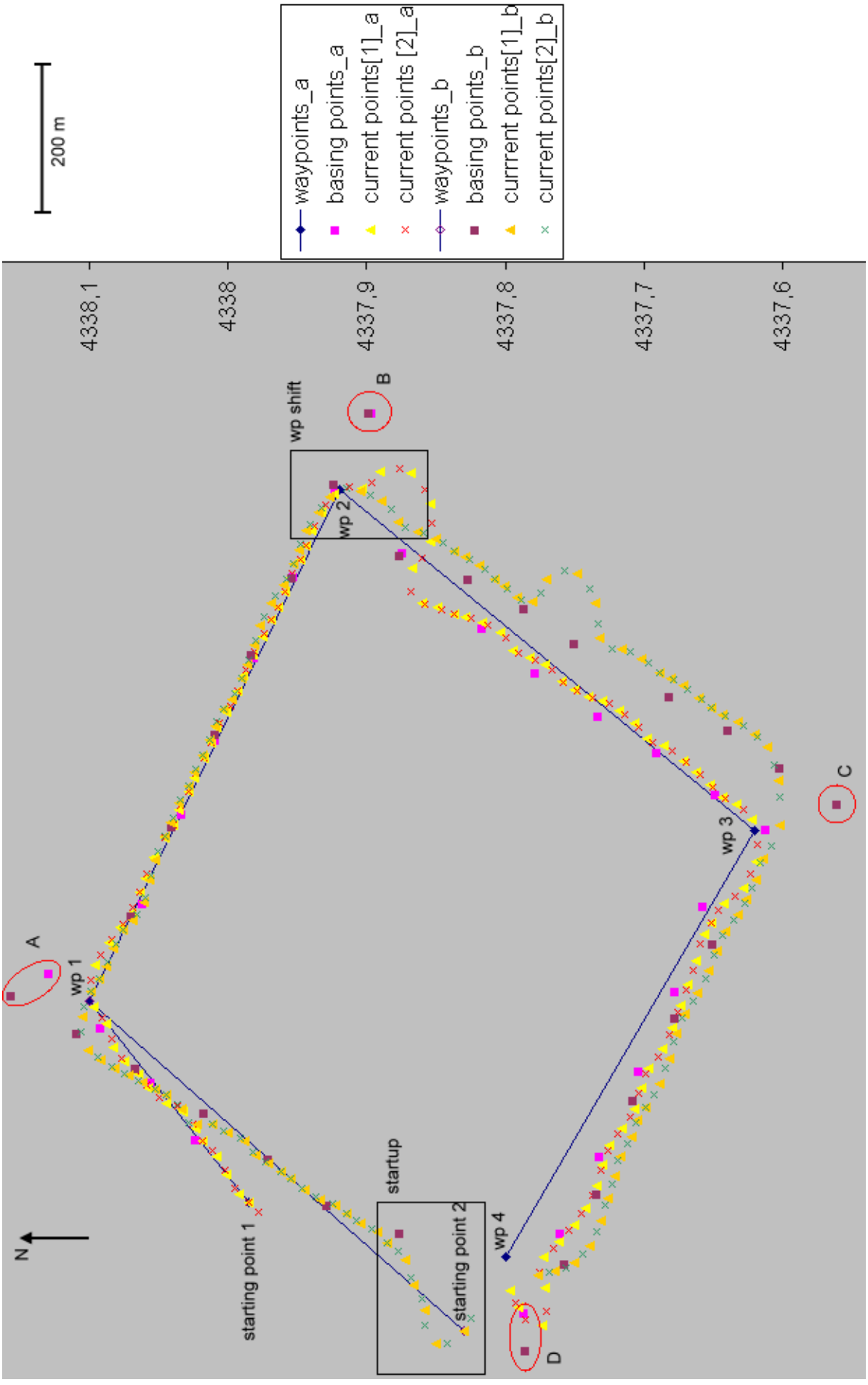


Figure B.1: *Waypoint following with basing points every 100 m*

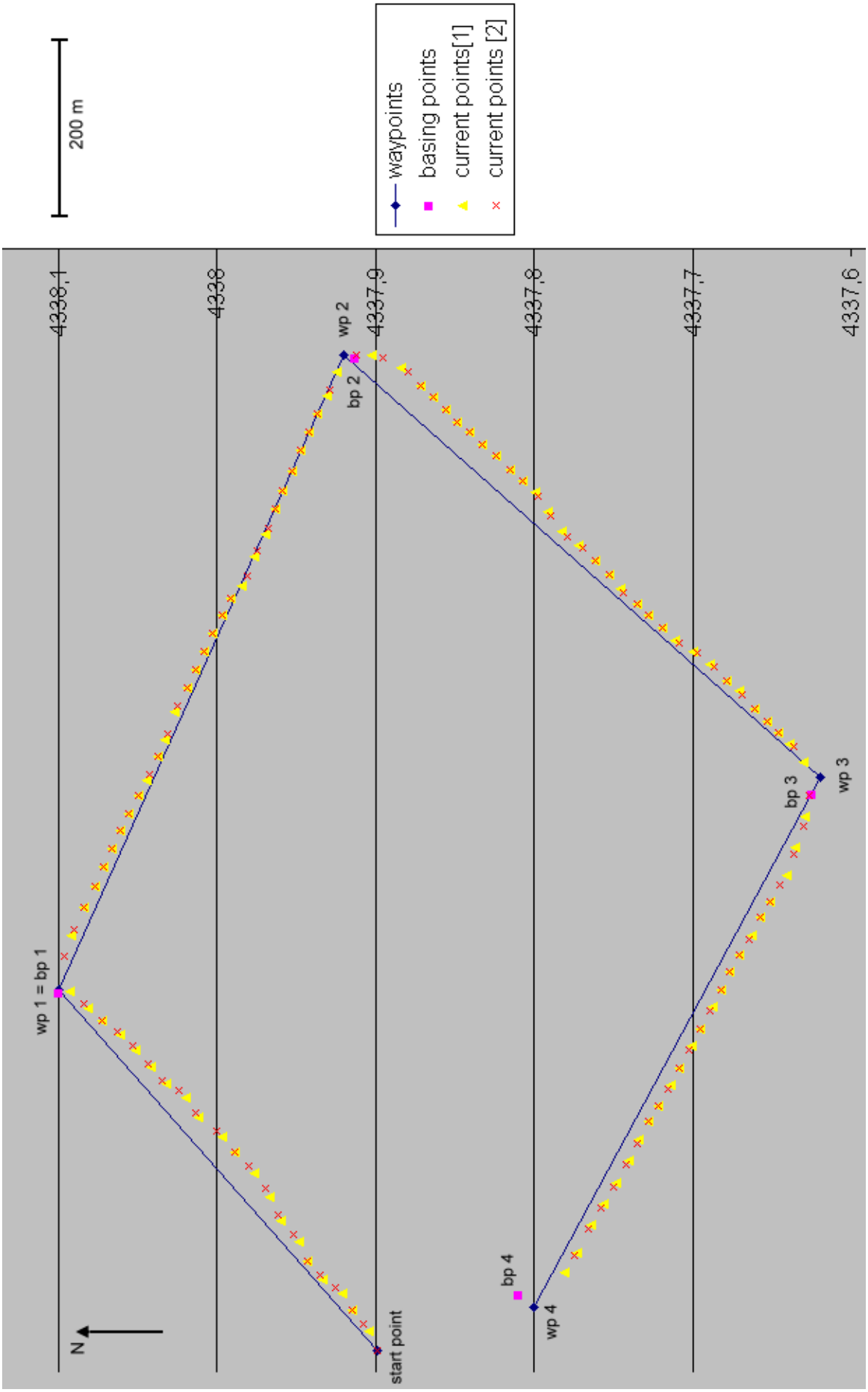


Figure B.2: *Waypoint following test with basingpoints on waypoints*

Appendix C

Schematics overview

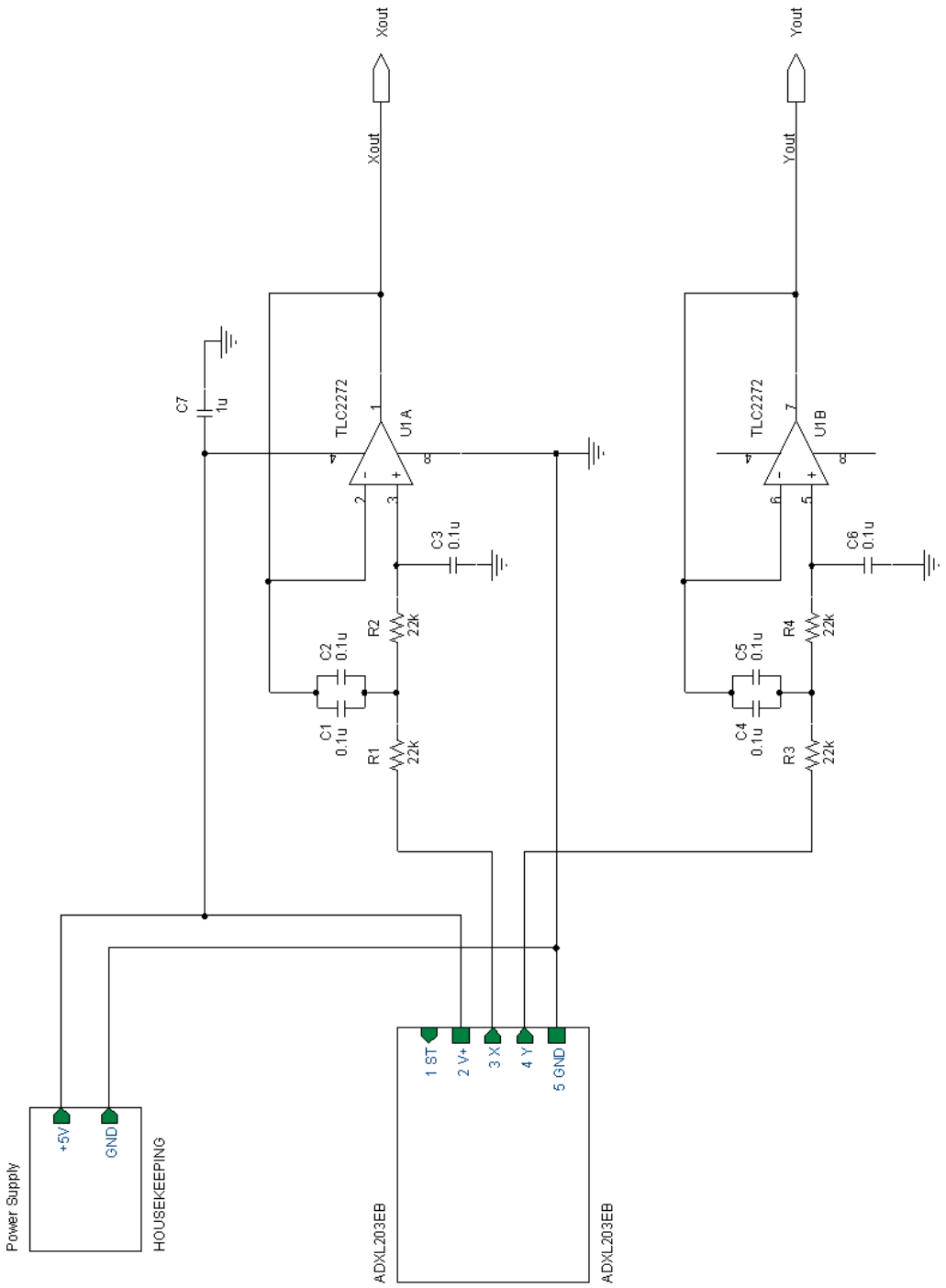


Figure C.1: *2nd order Butterworth Filter for the 2 axis tilt sensor*

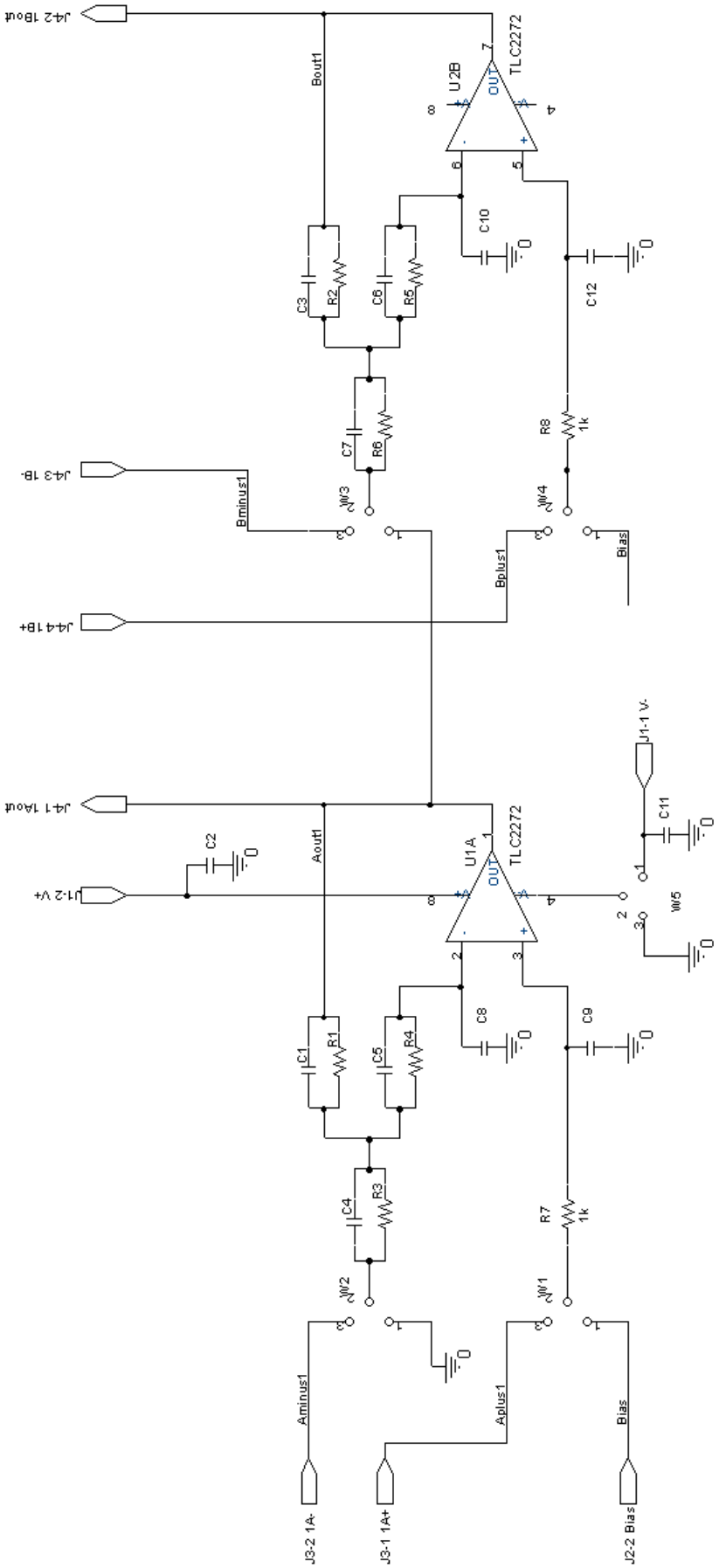


Figure C.2: *Conditioning circuit for the analog motor velocitiy and motor current inputs*

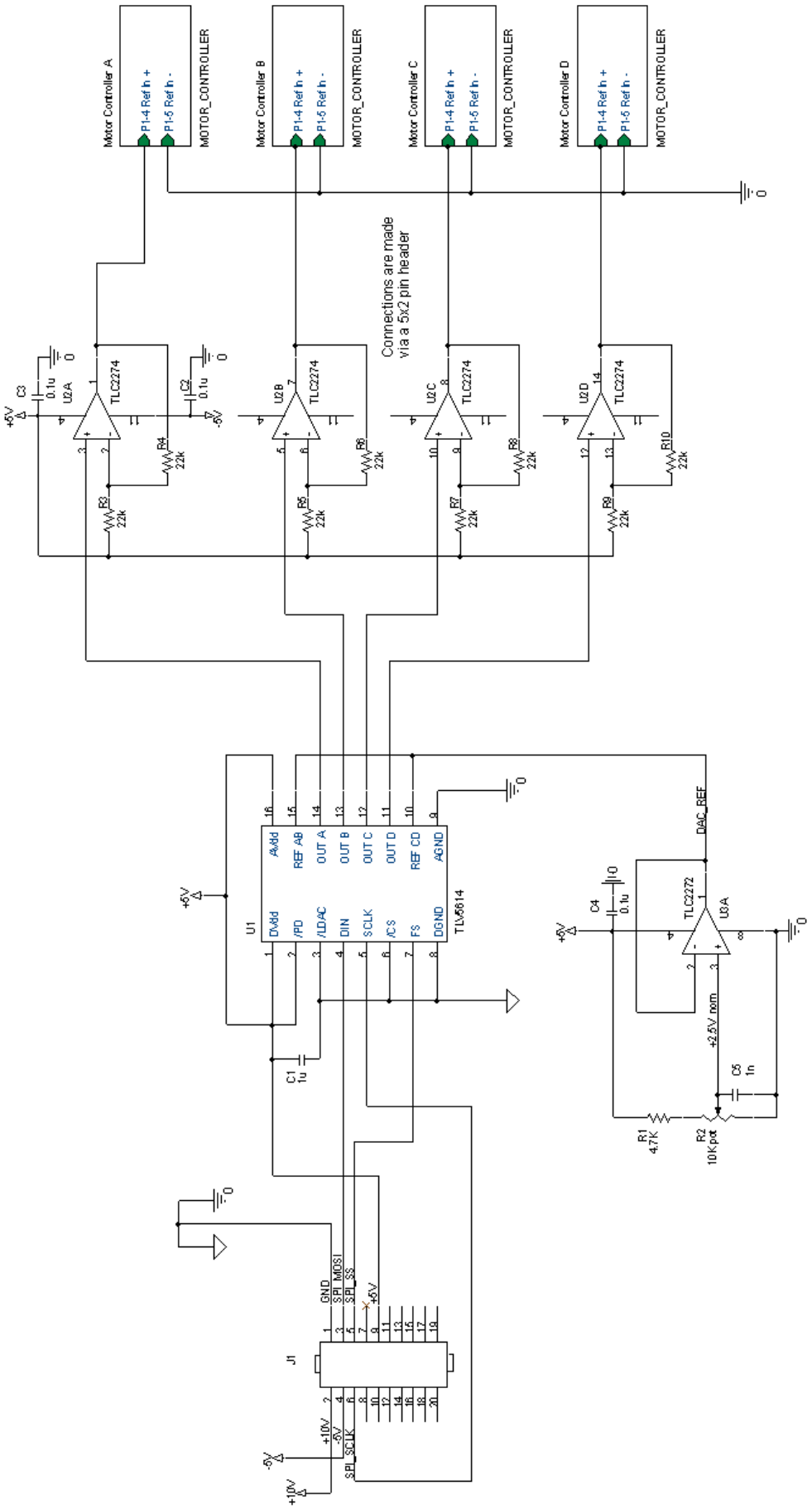


Figure C.3: *Schematic of DAC connections*

Appendix D

Source codes

D.1 analogin.lib

```
/*** Beginheader */
#ifndef __analogin_LIB
#define __analogin_LIB
/*** Endheader */

/* START LIBRARY DESCRIPTION *********************************************
analogin.lib
Goetz Dietrich, 2005
 version 0.91

 - no sequencing
 - 0..5V input range (0..2xRef)
 - sensor_high_centered new
 - tm_hc new (time check for high center) must be set to 0 in main
 - wheel_air new ( wheel that is in the air) must be set to 4 in main
 - tilt_hc[2] new ( reference tilt angle)

 will set up and read a Analog Devices EVAL-AD7490BC evaluation kit 12 bit A/D converto
 Connected to serial port B as outlined below:
 AD7490  RCM Jackrabbit
 GND     GND
 VDD     +5V
 SCLK    PB0
 CS      PD0
 DIN     PC4    TXB
 DOUT    PC5    RXB

ReadAD
read_sensors
sensor_range
sensor_high_centered
```

```
END DESCRIPTION **********************************************************/


/*** BeginHeader ReadAD */
 float ReadAD ( char *Command, int Samples);
 extern int Value;
 extern int Count, data_one, data_one_comp;
 extern char data[3];
 extern unsigned long i;
 extern float Voltage;
 extern unsigned long data_all;


#class auto

// SPI library definitions
//Power-on state:

#define WRITE 0x80 /* 1xxx xxxx xxxx xxxx write to conversion register */
#define XREF2 0x00 /* xxxx xxxx xxxx xx1x range from 0 V to 2x Vref V */
#define POWER 0x03 /* xxxx xx11 xxxx xxxx no power up delay */
////////////////////////////////////////////////////////////////////////////

// Channel Selection
#define IN00 0x00 /* xx00 00xx xxxx xxxx AIN0 */
#define IN01 0x04 /* xx00 01xx xxxx xxxx AIN1 */
#define IN02 0x08 /* xx00 10xx xxxx xxxx AIN2 */
#define IN03 0x0C /* 0011 AIN3 */
#define IN04 0x10 /* 0100 AIN4 */
#define IN05 0x14 /* 0101 AIN5 */
#define IN06 0x18 /* 0110 AIN6 */
#define IN07 0x1C /* 0111 AIN7 */
#define IN08 0x20 /* 1000 AIN8 */
#define IN09 0x24 /* 1001 AIN9 */
#define IN10 0x28 /* 1010 AIN10 */
#define IN11 0x2C /* 1011 AIN11 */
#define IN12 0x30 /* 1100 AIN12 */
#define IN13 0x34 /* 1101 AIN13 */
#define IN14 0x38 /* 1110 AIN14 */
#define IN15 0x3C /* 1111 AIN15 */
// Actions definitions
////////////////////////////////////////////////////////////////////////////


const char READ_AIN00[] =
{WRITE| POWER| IN00, XREF2};
const char READ_AIN01[] =
{WRITE| POWER| IN01, XREF2};
const char READ_AIN02[] =
{WRITE| POWER| IN02, XREF2};
const char READ_AIN03[] =
{WRITE| POWER| IN03, XREF2};
const char READ_AIN04[] =
{WRITE| POWER| IN04, XREF2};
const char READ_AIN05[] =
```

```
{WRITE| POWER| IN05, XREF2};
const char READ_AIN06[] =
{WRITE| POWER| IN06, XREF2};
const char READ_AIN07[] =
{WRITE| POWER| IN07, XREF2};
const char READ_AIN08[] =
{WRITE| POWER| IN08, XREF2};
const char READ_AIN09[] =
{WRITE| POWER| IN09, XREF2};
const char READ_AIN10[] =
{WRITE| POWER| IN10, XREF2};
const char READ_AIN11[] =
{WRITE| POWER| IN11, XREF2};
const char READ_AIN12[] =
{WRITE| POWER| IN12, XREF2};
const char READ_AIN13[] =
{WRITE| POWER| IN13, XREF2};
const char READ_AIN14[] =
{WRITE| POWER| IN14, XREF2};
const char READ_AIN15[] =
{WRITE| POWER| IN15, XREF2};


/*** EndHeader */

/* START FUNCTION DESCRIPTION ******************************
float ReadAD ( char *Command, int Samples ) <analogin.lib>

SYNTAX:  float ReadAD ( char *Command, int Samples );

DESCRIPTION:  will command the A/D to take a reading
       on the selected channel. It will take the average of the
  specified number of readings and convert the value to volts using the
    predefined scale factor.

PARAMETER1:   address of command bytes - must be 3 bytes
PARAMETER2:   (int) number of readings to average
RETURN VALUE:   float volts  needs to be scaled by scale factor

KEY WORDS:

END DESCRIPTION **************************************/

float ReadAD ( char *Command, int Samples )
 {

 int Count, data_one;
 int data_one_comp;                                  // twos complement if needed
 char data[2];                                       // conversion result as a 16 bit/2
 long data_all;                                      // all data samples added
 float Voltage;                                      // return value

 SPI_Binit();
 BitWrPortI ( PDDR, &PDDRShadow, 1, 0 ); // PD0 =1
 BitWrPortI ( PDDDR, &PDDDRShadow, 1, 0 ); // PD0 = output
 data_all = 0L;                                         // reset data_all
```

```
 for ( Count = 1; Count<= Samples; Count++ )          // loop for averaging the number
 {

 BitWrPortI ( PDDR, &PDDRShadow, 0, 0 ); // enable /CS
 SPI_BWrRd ( Command, &data, 2 );                    // write the command to the ADC an
 BitWrPortI ( PDDR, &PDDRShadow, 1, 0 ); // disable /CS
 data[0] = 0x0F & data[0];                    // extract the first four address bits
 data_one = data[0]*256 + data[1];            // convert the conversion result into an i
 if(data_one >= 2048)
 {
  data_one_comp =  ~(data_one); //+61441);
   data_one = 0x0FFF & data_one_comp;   // data_one = data_one_comp;
 } // end if
 data_all += (data_one); // update accumulator
 for (data_one_comp=0; data_one_comp<100; data_one_comp++); // cheap time delay
 }                 // end for
 Voltage = (float)data_all  / Samples;
 }                // end function

//////////////////////////////////////////////////////////////////////////////

/*** BeginHeader read_sensors */
void read_sensors();
#use SPI_B.lib
#use drive.lib
extern float scale_motor;
extern float scale_tilt;
extern float scale_velocity;
extern float output[15];
/*** EndHeader */

float scale_motor;             // scale factor for motor currents
float scale_tilt;              // scale factor for tilt sensors
float scale_velocity;
float output[15];

/* START FUNCTION DESCRIPTION ******************************
void read_sensors()    <analogin.lib>

SYNTAX:  void read_sensors;

DESCRIPTION:  will command the A/D to take a reading
       on the selected channels. It will take the average of the
  specified number of readings and convert the value to whatever
              the user wants by scale factors

PARAMETER1:   address of command bytes - must be 3 bytes
PARAMETER2:   (int) number of readings to average
RETURN VALUE:   float volts  needs to be scaled by scale factor

KEY WORDS:

END DESCRIPTION **************************************/

void read_sensors()
{
```

```
   int tilt_lim;
   tilt_lim = 45;
   scale_motor = 5/4096.0*2;          // 2A = 1V and 2.5 V reference
   scale_tilt = 5/4096.0;
   scale_velocity = 5/4096.0*120*60/2;        // 1V = 120Hz Hall frequency
   SPI_Binit;
   BitWrPortI ( PDDR, &PDDRShadow, 1, 0 ); // PD0 = 1
   BitWrPortI ( PDDDR, &PDDDRShadow, 1, 0 );  // PD0 = output
   output[0] = scale_motor*ReadAD(READ_AIN00, 400);       // motor current A
   output[1] = scale_motor*ReadAD(READ_AIN01, 400);       // motor current B
   output[2] = scale_motor*ReadAD(READ_AIN02, 400);       // motor current C
   output[3] = scale_motor*ReadAD(READ_AIN03, 400);       // motor current D
   output[4] = scale_velocity*ReadAD(READ_AIN04, 400);       // motor velocity A
   output[5] = scale_velocity*ReadAD(READ_AIN05, 400);       // motor velocity B
   output[6] = scale_velocity*ReadAD(READ_AIN06, 400);       // motor velocity C
   output[7] = scale_velocity*ReadAD(READ_AIN07, 400);       // motor velocity D
   output[8] = asin(scale_tilt*ReadAD(READ_AIN08, 400));       // motor tilt pitch
   output[9] = asin(scale_tilt*ReadAD(READ_AIN09, 400));       // motor tilt roll
   printf("currents A,B,C,D are: %f\n", output[0]);
   /*printf("velocities A,B,C,D are: %d, %d, %d\n", (int)output[4],
(int)output[5], (int)output[6]);
                                                    */


} // end read_sensors

/*** BeginHeader sensor_range */
int sensor_range();
#use drive.lib
extern float output[15];
extern int wp_start;
/*** EndHeader */

/* START FUNCTION DESCRIPTION ******************************
void sensor_range()    <analogin.lib>

SYNTAX:  void sensor_range();

DESCRIPTION:  will check the sensors readings and look if they exceed the limit
  and change drive mode


RETURN VALUE:


KEY WORDS:

END DESCRIPTION **********************************************/


int sensor_range()
{

if (abs(output[8]) >= tilt_lim || abs(output[9]) >= tilt_lim)
   {
      stop(motor_speed, motor_speed_increment);
```

```
      backwards_tilt();
      while(1)
      {
       costate
         {
          waitfor(DelayMs(4000));
            turn_right(motor_speed, angle);
            waitfor(DelayMs(18000));
         } // end costate
         costate
         {
          waitfor(DelayMs(22000));
            stop(motor_speed, motor_speed_increment);
            if(drive\_mode == 1)
            {
             forward_full();
            } // end if
            else
            {
             forward_partial();
            } // end if
            wp_start = 0;
            return 0;
         }    // end costate

      } // end while
   }
   else
   {
    return 1;
   }
} // end function

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader sensor_high_centered */
int sensor_high_centered(int *tm_hc, int *wheel_air);
extern float output[15];
extern float tilt_hc[2];
/*** EndHeader */



/* START FUNCTION DESCRIPTION ******************************
void sensor_high_centered(int tm_hc, int wheel_air)    <analogin.lib>

SYNTAX:  void sensor_high_centered(int tm_hc, int wheel_air);

DESCRIPTION:  will check the sensors readings and look for a high centered position (10
  and set drive_mode to 3 (high_centered)


RETURN VALUE:     1 - if high centered
0- otherwise


KEY WORDS:
```

```
END DESCRIPTION **********************************************/


int sensor_high_centered(int *tm_hc, int *wheel_air)
{
   int i; // count motor_speeds
   if(tm_hc == 10)
   {
    tm_hc = 0;
      wheel_air = 4;
      drive_mode = 3;
      return 1;
   } // end if
   else if(wheel_air <= 3)
   {
    if(output[wheel_air]<0.3 && output[wheel_air+4]>4800)
      {
       if(abs(tilt_hc[0]-output[8])<5 && abs(tilt_hc[1]-output[9])<5)
         {
          tm_hc++;
         } // end if
         else
       {
       tm_hc = 0;
          wheel_air = 4;
       } // end else
      } // end if
      return 0;
   } // end else if
   else if(wheel_air == 5)
   {
    tm_hc = 0;
      return 0;
   } // end else if
   else
   {
    for(i=0;i<4;i++)                    // count motor speeds
      {
       if(output[i]<0.3 && output[i+4]>4800)
         {
          tilt_hc[0] = output[8];
            tilt_hc[1] = output[9];
            tm_hc++;
            wheel_air = i;
            return 0;
         } // end if
      } // end for
   } // end else
} // end function

/*** BeginHeader */

#endif
/*** EndHeader */
```

D.2 drive.lib

```
/*** BeginHeader */
#ifndef __DRIVE_LIB
#define __DRIVE_LIB
/*** EndHeader */

/* START LIBRARY DESCRIPTION ******************************************
17mar2005
drive.lib
Goetz Dietrich, 2005
- switched motor_speed[0] with motor_speed[2]
- got_stuck not really implemented because no adc available
- backup_tilt implemented

functions to drive the robot in the wanted direction

faster_forwards
slower_forwards
turn_right
turn_left
stop
SwapBytes
SendToDAC
UpdateMotorOutput
DispStr
forward_full
forward_partial
backwards_tilt
manual_drive
wp_follow_full
wp_follow_partial
high_centered


END DESCRIPTION **************************************************************/

/*** BeginHeader */


#define SPI_SER_D
                              // Definition of the output channels
#define DACA 0x1000           // 12 bit control register filled up with zeros 0001 ...(
#define DACB 0x5000           // 0101 xxxx xxxx xxxx        is DACB
#define DACC 0x9000           // 1001 xxxx xxxx xxxx        is DACC
#define DACD 0xD000           // 1101 xxxx xxxx xxxx

#define Akey   65
#define DownArrow 25

const int zero_output = 2048;               // = 0 volts output
const int max_output = 1220;     //1220 = 3 volts   output
char key_input;

/*** EndHeader */
```

```
////////////////////////////////////////////////////////////////////////////
/*** BeginHeader faster_forwards */
int *faster_forwards(int *motor_speed, int motor_speed_increment);
/*** EndHeader */

/* START FUNCTION DESCRIPTION ****************************
faster_forwards()                        <drive.lib>

SYNTAX:  void faster_forwards();

DESCRIPTION:   speeds up the robot 5 percent for hitting the key"w"
               or slows down when driving backwards

PARAMETER1:  None

RETURN VALUE:   None

KEY WORDS:    drive

END DESCRIPTION ***************************************/
int *faster_forwards(int *motor_speed, int motor_speed_increment)
{
      if ((motor_speed[0] <= (100 - motor_speed_increment))    // if all motors are abl
         && (motor_speed[1] <= (100 - motor_speed_increment))
         && (motor_speed[2] <= (100 - motor_speed_increment))
         && (motor_speed[3] <= (100 - motor_speed_increment)))
      {
         motor_speed[0] += motor_speed_increment;          // rise them up to a 100%
         motor_speed[1] += motor_speed_increment;
         motor_speed[2] += motor_speed_increment;
         motor_speed[3] += motor_speed_increment;
         UpdateMotorOutput();                        // sends the new value of motor_sp
         return motor_speed;
      }                                          // end if

}                                                // end function

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader slower_forwards */
int *slower_forwards(int *motor_speed, int motor_speed_increment);
/*** EndHeader */
/* START FUNCTION DESCRIPTION ****************************
int *slower_forwards(int *motor_speed)                          <drive.lib>

SYNTAX:  int *slower_forwards(int motor_speed[4]);

DESCRIPTION:  slows down the robot 5 percent for hitting the key "s"

PARAMETER1:  None

RETURN VALUE:  None

KEY WORDS:   drive

END DESCRIPTION ***************************************/
int *slower_forwards(int *motor_speed, int motor_speed_increment)
```

```
{
      if(motor_speed[0] >= (motor_speed_increment - 100)        // if all motors are fa
               && (motor_speed[1] >= (motor_speed_increment - 100))
               && (motor_speed[2] >= (motor_speed_increment - 100))
               && (motor_speed[3] >= (motor_speed_increment - 100)))
      {
         motor_speed[0] -= motor_speed_increment;              // set motor speeds limi
         motor_speed[1] -= motor_speed_increment;
         motor_speed[2] -= motor_speed_increment;
         motor_speed[3] -= motor_speed_increment;
         UpdateMotorOutput();                                 // update DAC
         return motor_speed;
      }                                                       // end if
}                                                             // end function


////////////////////////////////////////////////////////////////////////////
/*** BeginHeader turn_right */
int *turn_right(int *motor_speed, int angle);
/*** EndHeader */

/* START FUNCTION DESCRIPTION ******************************
turn_right(int *motor_speed, int angle)           <drive.lib>

SYNTAX:  ;

DESCRIPTION:



PARAMETER1:

RETURN VALUE:

KEY WORDS:

END DESCRIPTION **************************************/
int *turn_right(int *motor_speed, int angle)
{
      if((motor_speed[2]>=100) && (motor_speed[1]>=100)
      && motor_speed[0]>=(angle-100)
      && motor_speed[3]>=(angle-100))
      {
         motor_speed[0] -= angle;
         motor_speed[3] -= angle;
         UpdateMotorOutput();
      }            // end if
      else if(motor_speed[0]<=(-100)
      && motor_speed[3]<=(-100)
      && motor_speed[2]<=(100-angle)
      && motor_speed[1]<=(100-angle))
      {
         motor_speed[2] += angle;
         motor_speed[1] += angle;
         UpdateMotorOutput();
      }           // end if
```

```
      else if(motor_speed[2]<=(100-(angle/2))
      && motor_speed[1]<=(100-(angle/2))
      && motor_speed[0]>=(angle/2-100)
      && motor_speed[3]>=(angle/2-100))
      {
         motor_speed[2] += angle/2;
         motor_speed[1] += angle/2;
         motor_speed[0] -= angle/2;
         motor_speed[3] -= angle/2;
         UpdateMotorOutput();
      }           // end if
         return motor_speed;
}                 // end function

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader turn_left */
int *turn_left(int *motor_speed, int angle);
/*** EndHeader */

/* START FUNCTION DESCRIPTION ****************************
int *turn_left(int *motor_speed, int angle)        <drive.lib>

SYNTAX:  ;

DESCRIPTION:



PARAMETER1:

RETURN VALUE:

KEY WORDS:

END DESCRIPTION ***************************************/
int *turn_left(int *motor_speed, int angle)
{
      if(motor_speed[0]>=100 && motor_speed[3]>=100
      && motor_speed[2]>=(angle-100)
      && motor_speed[1]>=(angle-100))
      {
         motor_speed[2] -= angle;
         motor_speed[1] -= angle;
         UpdateMotorOutput();
      }           // end if
      else if(motor_speed[2]<=-100
      && motor_speed[1]<=-100
      && motor_speed[0]<=(100-angle)
      && motor_speed[3]<=(100-angle))
      {
         motor_speed[0] += angle;
         motor_speed[3] += angle;
         UpdateMotorOutput();
      }          // end if
      else if(motor_speed[0]<=(100-(angle/2))
      && motor_speed[3]<=(100-(angle/2))
```

```
      && motor_speed[2]>=((angle/2)-100)
      && motor_speed[1]>=((angle/2)-100))
      {
         motor_speed[2] -= angle/2;
         motor_speed[1] -= angle/2;
         motor_speed[0] += angle/2;
         motor_speed[3] += angle/2;
         UpdateMotorOutput();
      }            // end if
      return motor_speed;
}                  // end function

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader stop */
int *stop(int *motor_speed, int motor_speed_increment);
/*** EndHeader */

/* START FUNCTION DESCRIPTION ******************************
int *stop(int *motor_speed)                 <drive.lib>

SYNTAX:  ;

DESCRIPTION:



PARAMETER1:

RETURN VALUE:

KEY WORDS:

END DESCRIPTION **********************************************/
int *stop(int *motor_speed, int motor_speed_increment)
{
   int k;
   while (1){
      if((motor_speed[0]>=20)&&(motor_speed[1]>=20)
      &&(motor_speed[2]>=20)&&(motor_speed[3]>=20))
      {
      costate {
         waitfor(DelayMs(40));
         slower_forwards(motor_speed, motor_speed_increment);
         UpdateMotorOutput();
         }  // end costate
      }     // end if
      else if((motor_speed[0]<=-20)&&(motor_speed[1]<=-20)
      &&(motor_speed[2]<=-20)&&(motor_speed[3]<=-20))
      {
      costate {
         waitfor (DelayMs(40));
         faster_forwards(motor_speed, motor_speed_increment);
         UpdateMotorOutput();
         }  // end costate
      }     // end if
      else if(motor_speed[0]>=5&&motor_speed[1]>=5
```

```
      && motor_speed[2]<=-5&&motor_speed[3]<=-5)
      {
      costate {
         waitfor(DelayMs(40));
         turn_left(motor_speed, angle);
         UpdateMotorOutput();
         }  // end costate
      }     // end if
      else if(motor_speed[2]>=5&&motor_speed[3]>=5
      && motor_speed[0]<=-5&&motor_speed[1]<=-5)
      {
      costate {
         waitfor(DelayMs(40));
         turn_right(motor_speed, angle);
         UpdateMotorOutput();
         }  // end costate
      }     // end if
      else
      {
      for(k=0;k<4;k++)
         {
         motor_speed[k]=0;
         UpdateMotorOutput();
         }  //end for
      return motor_speed;
      }     // end else
   }        // end while
}           // end main

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader DispStr */
void DispStr(int x, int y, char *s);
extern int x;
extern int y;
/*** EndHeader */
int x;
int y;
/* START FUNCTION DESCRIPTION ******************************
void DispStr( int x, int y, char *s)            <drive.lib>

SYNTAX:  ;

DESCRIPTION:



PARAMETER1:

RETURN VALUE:

KEY WORDS:

END DESCRIPTION **********************************************/
// Set the STDIO cursor location and display a string
void DispStr(int x, int y, char *s)
{
```

```
   x += 0x20;
   y += 0x20;
   printf ("\x1B=%c%c%s", x, y, s);
}

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader SwapBytes */
int SwapBytes (int value );
extern int i0;
/*** EndHeader */
int i0;
/* START FUNCTION DESCRIPTION ****************************
SwapBytes                          <drive.lib>

SYNTAX:  int SwapBytes (int value) ;

DESCRIPTION:  The function SwapBytes is used to swap the order of the two
              byte output value.  This is necessary because the Rabbit and
              Dynamic C are Little Endian - the LS byte is sent first.  The
              MAX 536 requires that the MS byte be transmitted first.



PARAMETER1:   2 byte value

RETURN VALUE: swapped 2 byte value

KEY WORDS:

END DESCRIPTION **********************************************/


int SwapBytes ( int value )
{  int i0;
   i0 = (value<<8) & 0xFF00;  // put low byte into high byte
   i0 |= (value>>8) & 0x00FF; // put high byte into low byte
   return i0;
}
////////////////////////////////////////////////////////////////////////////
/*** BeginHeader SendToDAC */
void SendToDAC (int message );

#ifdef SPI_SER_B
#undef SPI_SER_B
#define SPI_SER_D
#endif
#ifndef SPI_SER_D
#define SPI_SER_D
#endif
#ifdef SPI_SER_D
#use SPI.lib
#endif

/*** EndHeader */

/* START FUNCTION DESCRIPTION ****************************
```

```
SendToDAC (int message )                  <drive.lib>

SYNTAX: void SendToDAC (int message );

DESCRIPTION: sends message to the MAX536

PARAMETER1: message wanted to be send to the MAX536

RETURN VALUE:  NONE

KEY WORDS:

END DESCRIPTION ***************************************/


void SendToDAC ( int message )
{
   WrPortI ( PBDDR, &PBDDRShadow, 0xFF ); // PB = all output
   BitWrPortI ( PBDR, &PBDRShadow, 0, 2 );   // CS = 0 enable CS      on PB2
   SPIWrite( &message, 2 );
   BitWrPortI ( PBDR, &PBDRShadow, 1, 2 );   // CS =y 1 disable CS

}

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader UpdateMotorOutput */

void UpdateMotorOutput ();

extern char display1[128];
extern char display2[128];
extern char display3[128];
extern char display4[128];
extern char fstring[256];

#ifdef SPI_SER_B
#undef SPI_SER_B
#define SPI_SER_D
#endif

#ifndef SPI_SER_D
#define SPI_SER_D
#endif

#ifdef SPI_SER_D
#use SPI.lib
#endif

/*** EndHeader */
char display1[128];
char display2[128];
char display3[128];
char display4[128];

/* START FUNCTION DESCRIPTION ****************************
UpdateMotorOutput ()               <drive.lib>
```

```
SYNTAX: void UpdateMotorOutput () ;

DESCRIPTION:



PARAMETER1:

RETURN VALUE:

KEY WORDS:

END DESCRIPTION ***************************************/
void UpdateMotorOutput ()
{
   SPIinit ();
   SendToDAC(SwapBytes((int)(zero_output+((long)max_output*motor_speed[0]/100))|DACA));
   SendToDAC(SwapBytes((int)(zero_output+((long)max_output*motor_speed[1]/100))|DACB));
   SendToDAC(SwapBytes((int)(zero_output+((long)max_output*motor_speed[2]/100))|DACC));
   SendToDAC(SwapBytes((int)(zero_output+((long)max_output*motor_speed[3]/100))|DACD));
   printf("motorspeeds A,B,C,D are: %d, %d, %d, %d\n", motor_speed[0], motor_speed[1],
                                                       motor_speed[2], motor_speed[3]);
}

////////////////////////////////////////////////////////////////////////////

/*** BeginHeader forward_full */
void forward_full();

/*** EndHeader */

/* START FUNCTION DESCRIPTION ****************************
void forward_full                   <drive.lib>

SYNTAX: void forward_full() ;

DESCRIPTION: checks if motor speeds are on 100 and sets them

PARAMETER1:

RETURN VALUE:

KEY WORDS:

END DESCRIPTION ***************************************/

void forward_full()
{
   while(motor_speed[0] != 100 && motor_speed[3] != 100)
   {
      costate
      {
         faster_forwards(motor_speed, motor_speed_increment);
         waitfor (DelayMs(200));
      }     // end costate
```

```
   }     // end while

}     // end function

////////////////////////////////////////////////////////////////////////////

/*** BeginHeader forward_partial */
void forward_partial();

/*** EndHeader */

/* START FUNCTION DESCRIPTION ******************************
void forward_partial                  <drive.lib>

SYNTAX: void forward_partial() ;

DESCRIPTION: checks if motor speeds are on 100 and sets them

PARAMETER1:

RETURN VALUE:

KEY WORDS:

END DESCRIPTION **********************************************/

void forward_partial()
{
   while(motor_speed[0] != 60 && motor_speed[3] != 60)
   {

         costate
         {
            if(motor_speed[1] <= 50 && motor_speed[2] <= 50)
            {
               faster_forwards(motor_speed, motor_speed_increment);
            }     // end if
            else if(motor_speed[0] >=70 && motor_speed[3] >= 70)
            {
               slower_forwards(motor_speed, motor_speed_increment);
            }     // end else if
            waitfor (DelayMs(200));
         }     // end costate
   }     // end while

}     // end function


////////////////////////////////////////////////////////////////////////////

/*** BeginHeader backwards_tilt */
void backwards_tilt();

/*** EndHeader */

/* START FUNCTION DESCRIPTION ******************************
```

```
void backwards_tilt                    <drive.lib>

SYNTAX: void backwards_tilt() ;

DESCRIPTION: backs up Cool Robot in case of high tilt sensors

PARAMETER1:

RETURN VALUE:

KEY WORDS:

END DESCRIPTION ***************************************/

void backwards_tilt()
{
   while(motor_speed[0] != -100 && motor_speed[3] != -100)
   {
      costate
      {
         slower_forwards(motor_speed, motor_speed_increment);
         waitfor (DelayMs(200));
      }     // end costate
   }     // end while

}     // end function

////////////////////////////////////////////////////////////////////////////////

/*** BeginHeader manual_drive */
int manual_drive(char *drive_string);
extern int drive_mode;
/*** EndHeader */
const char cmp_drive[] = "wasdqp";
/* START FUNCTION DESCRIPTION ****************************************
manual_drive                              <drive.lib>

SYNTAX:

KEYWORDS:

DESCRIPTION:

PARAMETER1:
PARAMETER2:

RETURN VALUE:



SEE ALSO:

END DESCRIPTION ***************************************************/

int manual_drive(char *drive_string)
{
```

```
   int count_a,count_d,count_s,count_w,x;
   //count_a = 0;
   //count_d = 0;
   //count_s = 0;
   //count_w = 0;
   x = 0;
   send_event = 6;

   for(x=0;x<strlen(drive_string);x++)
   {
      if(drive_string[x] == cmp_drive[0])       // "w" - accelerate robot
      {
         faster_forwards(motor_speed, motor_speed_increment);
      }
      else if(drive_string[x] == cmp_drive[1]) // "a" - take a left turn
      {
         turn_left(motor_speed, angle);
      }
      else if(drive_string[x] == cmp_drive[2]) // "s" - slow down robot
      {
         slower_forwards(motor_speed, motor_speed_increment);
      }
      else if(drive_string[x] == cmp_drive[3]) // "d" - take a right turn
      {
         turn_right(motor_speed, angle);
      }
      else if(drive_string[x] == cmp_drive[4]) // "q" - stop robot
      {
         stop(motor_speed, motor_speed_increment);
      }
      else if(drive_string[x] == cmp_drive[5]) // "p" - exit manual drive mode
      {
         drive_mode = 1;
         wp_start = 0;
      } // end elseif
   } // end for
} // end manual_drive

////////////////////////////////////////////////////////////////////////////

/*** BeginHeader wp_follow_full */
int wp_follow_full();
extern char in_stri[128];
extern int tm_hc;
extern int wheel_air;
extern int wp_start;
extern int GPS_inv_limit;
extern int tm_nav;
extern GPSPosition curr_p2;
/*** EndHeader */

GPSPosition curr_p2;
/* START FUNCTION DESCRIPTION ********************************************
int wp_follow_full()                      <drive.lib>

SYNTAX:
```

```
KEYWORDS:

DESCRIPTION:

PARAMETER1:
PARAMETER2:

RETURN VALUE:



SEE ALSO:

END DESCRIPTION **********************************************************/

int wp_follow_full()
{
int count_invalid;
   costate
   {
      waitfor(DelayMs(2000));
      getgps(in_stri);
      if(wp_start == 0)
      {
         count_invalid = 0;
       while(count_invalid != 60)
{
costate
    {
    waitfor(DelayMs(1000));
       count_invalid++;
       getgps(in_stri);
             if(gps_get_position(&curr_p2, in_stri) == 0)
   {
                break;
              }
             if (gps_get_position(&curr_p2, in_stri) == -1)
       {
       sprintf(out_string,"GPS parsing error\n\r");
       send_event = 5;

       } // end if
       if (gps_get_position(&curr_p2, in_stri) == -2)
       {
       sprintf(out_string,"GPS sentence invalid\n\r");
       send_event = 5;

       } // end else if
       if(count_invalid == 60)
       {
       drive_mode = 5;
                return 0;
       } // end if
    } // end costate
} // end while
```

```
      } // end if
      forward_full();
      //read_sensors();
   }     // end costate
   costate
   {
      waitfor(DelayMs(1000));
      // sensor_range();
      // sensor_high_centered(tm_hc, wheel_air);
   } // end costate
   costate
   {
      waitfor(DelayMs(tm_nav*1000));
      navigate(in_stri);
   }     // end costate
}     // end wp_follow_full

////////////////////////////////////////////////////////////////////////////

/*** BeginHeader wp_follow_partial */
void wp_follow_partial();
/*** EndHeader */

/* START FUNCTION DESCRIPTION ********************************************
wp_follow_partial()                     <drive.lib>

SYNTAX:

KEYWORDS:

DESCRIPTION:

PARAMETER1:
PARAMETER2:

RETURN VALUE:



SEE ALSO:

END DESCRIPTION **********************************************************/

void wp_follow_partial()
{
   costate
   {
      waitfor(DelayMs(2000));
      getgps(in_stri);
      forward_partial();
      read_sensors();
   }     // end costate
   costate
   {
      waitfor(DelayMs(tm_nav*1000));
      navigate(in_stri);
```

```
   }     // end costate
}     // end wp_follow_partial

////////////////////////////////////////////////////////////////////////////

/*** BeginHeader high_centered */
int high_centered(char *in_string);
extern int drive_mode;
/*** EndHeader */

/* START FUNCTION DESCRIPTION ********************************************
high_centered(char *in_string)                              <drive.lib>

SYNTAX:

KEYWORDS:

DESCRIPTION:     drive mode called while high centered with motor speeds = 0;
                 has to be tested
PARAMETER1:


RETURN VALUE:



SEE ALSO:

END DESCRIPTION **********************************************************/

int high_centered(char *in_string)
{
int stk;
while(1)
   {

    stk = 0;
    if(strncmp((in_string), "exit", 4) == 0)  // cmd for exiting got_stuck
    {
       drive_mode = 1;
       return 1;
    }     // end if
    while(stk <= 9)
    {

       costate
       {
         waitfor(DelayMs(100));
          slower_forwards(motor_speed, motor_speed_increment);
          stk++;
       }     // end costate
    }     // end while
    stk = 0;
      costate
      {
       waitfor(DelayMs(12000));
```

```
       while(stk <= 19)
    {
        costate
       {
          waitfor(DelayMs(100));
               faster_forwards(motor_speed, motor_speed_increment);
               stk++;
            }     // end costate
    }     // end while
    } // end costate
   } // end while
}     // end got_stuck

/*** BeginHeader */
#endif
/*** EndHeader */
```

D.3 gps.lib

```
/*** BeginHeader */
#ifndef __GPS_LIB
#define __GPS_LIB
/*** EndHeader */

/* START LIBRARY DESCRIPTION ********************************************
23mar2005
gps.lib
ZWorld, 2001
Goetz Dietrich, 2005
- bearing calculation changed to double ( arccos transfered to arctan)
- bearing calculation changed to 0°/180° case

functions for parsing NMEA-0183 location data from a GPS receiver.
Also has functions for computing distances, bearings and to calculate
basing points:

gps_get_position
gps_get_utc
gps_ground_distance
gps_bearing
gps_basing_point
getgps

END DESCRIPTION **********************************************************/

/*** BeginHeader */

//This structure holds geographical position as reported by a GPS receiver
//use the gps_get_position function below to set the fields
typedef struct {
int lat_degrees;
int lon_degrees;
float lat_minutes;
float lon_minutes;
char lat_direction;
char lon_direction;
   char sog;     //speed over ground
   float tog;            //track over ground
} GPSPosition;

//in km

#define GPS_EARTH_RADIUS 6356      // in km
#define dbp 0.25 // distance to next basing point in km

/*** EndHeader */

/*** BeginHeader gps_parse_coordinate */
int gps_parse_coordinate(char *coord, int *degrees, float *minutes);
/*** EndHeader */
```

```
//helper function for splitting xxxxx.xxxx into degrees and minutes
//returns 0 if succeeded
nodebug int gps_parse_coordinate(char *coord, int *degrees, float *minutes)
{
auto char *decimal_point;
auto char temp;
auto char *dummy;

decimal_point = strchr(coord, '.');
if(decimal_point == NULL)
return -1;
temp = *(decimal_point - 2);
*(decimal_point - 2) = 0; //temporary terminator
*degrees = atoi(coord);
*(decimal_point - 2) = temp; //reinstate character
*minutes = strtod(decimal_point - 2, &dummy);
return 0;
}

/*** BeginHeader gps_get_position */
int gps_get_position(GPSPosition *newpos, char *sentence);
/*** EndHeader */

/* START FUNCTION DESCRIPTION ********************************************
gps_get_position                  <gps.lib>

SYNTAX:  int gps_get_position(GPSPositon *newpos, char *sentence);

KEYWORDS:      gps

DESCRIPTION:   Parses a sentence to extract position data.
This function is able to parse any of the following
GPS sentence formats: GGA, GLL, RMC

PARAMETER1:    newpos - a GPSPosition structure to fill
PARAMETER2: sentence - a string containing a line of GPS data
in NMEA-0183 format

RETURN VALUE:  0 - success
-1 - parsing error
-2 - sentence marked invalid

SEE ALSO:

END DESCRIPTION **********************************************************/

//can parse GGA, GLL, or RMC sentence
int gps_get_position(GPSPosition *newpos, char *sentence)
{
auto int i, tg;
   auto char togg[5];
   auto char *dummy;

if(strlen(sentence) < 4)
return -1;
if(strncmp(sentence, "$GPGGA", 6) == 0)
```

```
{
//parse GGA sentence
for(i = 0;i < 11;i++)
{
sentence = strchr(sentence, ',');
if(sentence == NULL)
return -1;
sentence++; //first character in field
//pull out data
if(i == 1) //latitude
{
if( gps_parse_coordinate(sentence,
    &newpos->lat_degrees,
    &newpos->lat_minutes)
  )
{
return -1; //get_coordinate failed
}
}
if(i == 2) //lat direction
{
newpos->lat_direction = *sentence;
}
if(i == 3) // longitude
{
if( gps_parse_coordinate(sentence,
    &newpos->lon_degrees,
    &newpos->lon_minutes)
  )
{
return -1; //get_coordinate failed
}
}
if(i == 4) //lon direction
{
newpos->lon_direction = *sentence;
}
if(i == 5) //link quality
{
if(*sentence == '0')
return -2;
}
}
}
else if(strncmp(sentence, "$GPGLL", 6) == 0)
{
//parse GLL sentence
for(i = 0;i < 6;i++)
{
sentence = strchr(sentence, ',');
if(sentence == NULL)
{
//handle short GLL sentences from Garmin receivers
if(i > 3) break;
return -1;
}
```

```
sentence++; //first character in field
//pull out data
if(i == 0) //latitude
{
if( gps_parse_coordinate(sentence,
    &newpos->lat_degrees,
    &newpos->lat_minutes)
  )
{
return -1; //get_coordinate failed
}
}
if(i == 1) //lat direction
{
newpos->lat_direction = *sentence;
}
if(i == 2) // longitude
{
if( gps_parse_coordinate(sentence,
    &newpos->lon_degrees,
    &newpos->lon_minutes)
  )
{
return -1; //get_coordinate failed
}
}
if(i == 3) //lon direction
{
newpos->lon_direction = *sentence;
}
if(i == 5) //link quality
{
if(*sentence != 'A')
return -2;
}
}
}
else if(strncmp(sentence, "$GPRMC", 6) == 0)
{
//parse RMC sentence
for(i = 0;i < 11;i++)
{
sentence = strchr(sentence, ',');
if(sentence == NULL)
return -1;
sentence++; //first character in field
//pull out data
if(i == 1) //link quality
{
if(*sentence != 'A')
return -2;
}
if(i == 2) //latitude
{
if( gps_parse_coordinate(sentence,
    &newpos->lat_degrees,
```

```
    &newpos->lat_minutes)
  )
{
return -1; //get_coordinate failed
}
}
if(i == 3) //lat direction
{
            if(*sentence == 'N' || *sentence == 'S')
            {
             newpos->lat_direction = *sentence;
            } // end if
            else
            return -2;
}
if(i == 4) // longitude
{
if( gps_parse_coordinate(sentence,
    &newpos->lon_degrees,
    &newpos->lon_minutes)
  )
{
return -1; //get_coordinate failed
}
}
if(i == 5) //lon direction
{
          if(*sentence == 'W' || *sentence == 'E')
            {
newpos->lon_direction = *sentence;
            } // end if
            else
            return -2;
         }
         if(i == 6) //speed over ground, knots
{
newpos->sog = *sentence;
}
         if(i == 7) //track over ground, degrees true
{
          for(tg=1;tg<6;tg++)
togg[tg-1] = *(sentence + tg);
            newpos->tog = strtod(togg, &dummy);
         }
    }
}
else
{
return -1; //unknown sentence type
}
return 0;
}

/*** BeginHeader gps_get_utc */
int gps_get_utc(struct tm *newtime, char *sentence);
/*** EndHeader */
```

```
/* START FUNCTION DESCRIPTION ********************************************
gps_get_utc                  <gps.lib>

SYNTAX:  int gps_get_utc(struct tm *newtime, char *sentence);

KEYWORDS:      gps

DESCRIPTION:   Parses an RMC sentence to extract time data

PARAMETER1: newtime - tm structure to fill with new UTC time
PARAMETER2: sentence - a string containing a line of GPS data
in NMEA-0183 format(RMC sentence)

RETURN VALUE:  0 - success
-1 - parsing error
-2 - sentence marked invalid

SEE ALSO:

END DESCRIPTION **********************************************************/

nodebug int gps_get_utc(struct tm *newtime, char *sentence)
{
int i;
char temp_str[3];
unsigned long epoch_sec;
temp_str[2] = 0; //2 character string
if(strncmp(sentence, "$GPRMC", 6) == 0)
{
//parse RMC sentence
for(i = 0;i < 11;i++)
{
sentence = strchr(sentence, ',');
if(sentence == NULL)
return -1;
sentence++; //first character in field
//pull out data
if(i == 0)
{
strncpy(temp_str, sentence, 2);
newtime->tm_hour = atoi(temp_str);
strncpy(temp_str, sentence+2, 2);
newtime->tm_min = atoi(temp_str);
strncpy(temp_str, sentence+4, 2);
newtime->tm_sec = atoi(temp_str);
}
if(i == 1) //link quality
{
if(*sentence != 'A')
return -2;
}
if(i == 8) //lon direction
{
strncpy(temp_str, sentence, 2);
newtime->tm_mday = atoi(temp_str);
```

```
strncpy(temp_str, sentence+2, 2);
newtime->tm_mon = atoi(temp_str);
strncpy(temp_str, sentence+4, 2);
newtime->tm_year = 100 + atoi(temp_str);
}
}
//convert back and forth to get weekday
epoch_sec = mktime(newtime);
mktm(newtime, epoch_sec);
return 0;
}
else
{
return -1; //unknown sentence type
}
}

/*** BeginHeader gps_ground_distance */
float gps_ground_distance(GPSPosition *a, GPSPosition *b);
#use DoublePrecision.lib
/*** EndHeader */

/* START FUNCTION DESCRIPTION ****************************************
gps_ground_distance               <gps.lib>

SYNTAX: float gps_ground_distance(GPSPosition *a, GPSPosition *b);

KEYWORDS:      gps

DESCRIPTION:   Calculates ground distance(in km) between to
               geographical points. (Uses spherical earth model)

PARAMETER1: a - first point
PARAMETER2: b - second point

RETURN VALUE:  distance in kilometers

SEE ALSO:

END DESCRIPTION ***************************************************/

float gps_ground_distance(GPSPosition *a, GPSPosition *b)
{
float angle, pi;
float lat_a, lon_a, lat_b, lon_b;
   _double dummy00, diss;
   _double lat_x, lat_y, lon_x, lon_y;
   pi = 3.141592654;

   lat_a = a->lat_degrees + a->lat_minutes/60;
if(a->lat_direction == 'S')
lat_a = -lat_a;
lat_a = lat_a * PI / 180;
lon_a = a->lon_degrees + a->lon_minutes/60;
  if(a->lon_direction == 'E')
lon_a = -lon_a;
```

```
lon_a = lon_a * PI / 180;

lat_b = b->lat_degrees + b->lat_minutes/60;
if(b->lat_direction == 'S')
lat_b = -lat_b;
lat_b = lat_b * PI / 180;
lon_b = b->lon_degrees + b->lon_minutes/60;
  if(b->lon_direction == 'E')
lon_b = -lon_b;
lon_b = lon_b * PI / 180;

   lat_x = dpFloat2Double(lat_a);
   lat_y = dpFloat2Double(lat_b);
   lon_x = dpFloat2Double(lon_a);
   lon_y = dpFloat2Double(lon_b);
   dummy00 = dpAdd(dpMul(dpSine(lat_x),dpSine(lat_y)),dpMul(dpMul(dpCosine(lat_x),dpCos
   //dummy00 = dpSin(lat_a) * dpSin(lat_b) + dpCos(lat_a) * dpCos(lat_b) *dpCos(lon_a-l
   diss = dpAdd(dpArctan(dpDiv(dpNeg(dummy00),
dpSqrt(dpAdd(dpMul(dpNeg(dummy00),dummy00),dpMakeNum(0x3ff00000,0x0)/*1*/))))),dpMul(dpM
   //angle = dpAtan(-dummy00/dpSqrt(-dummy00*dummy00+1))+2*dpAtan(1)
   diss = dpMul(diss,dpMakeNum(0x40b8d200,0x0)/*6354;*/);
   //    angle = angle * 6354;
   angle = dpDouble2Float(diss);

}



/*** BeginHeader gps_bearing */
float gps_bearing(GPSPosition *c, GPSPosition *d, float dist);
/*** EndHeader */

/* START FUNCTION DESCRIPTION ****************************************
gps_bearing                <gps.lib>

SYNTAX: float gps_bearing(GPSPosition *a, GPSPosition *b, dist);

KEYWORDS:      gps

DESCRIPTION:   Calculates bearing(in degree) from one geographical point a
               to a geographical point b. (Uses spherical earth model)

PARAMETER1: a - first point
PARAMETER2: b - second point
PARAMETER3: dist - ground distance between the two points a b

RETURN VALUE:  bearing in degrees

SEE ALSO:

END DESCRIPTION ***************************************************/

float gps_bearing(GPSPosition *c, GPSPosition *d, float dist)
{
float bearing, pi, lon_dif, lon_diflim;
float lat_c, lon_c, lat_d, lon_d;
```

```
   _double dummy00, dista, dummy01;
   _double lat_x, lat_y, lon_x, lon_y;
   pi = 3.141592654;

   lat_c = c->lat_degrees + c->lat_minutes/60;
if(c->lat_direction == 'S')
lat_c = -lat_c;
lat_c = lat_c * PI / 180;
lon_c = c->lon_degrees + c->lon_minutes/60;
  if(c->lon_direction == 'E')
lon_c = -lon_c;
lon_c = lon_c * PI / 180;
   lat_d = d->lat_degrees + d->lat_minutes/60;
if(d->lat_direction == 'S')
lat_d = -lat_d;
lat_d = lat_d * PI / 180;
lon_d = d->lon_degrees + d->lon_minutes/60;
  if(d->lon_direction == 'E')
lon_d = -lon_d;
lon_d = lon_d * PI / 180;

   if (cos(lat_c) < 0.0001)      // Small number
    if (lat_c > 0)
       bearing = 180;           // Starting from N pole
      else bearing = 360;        // Starting from S pole

   dist = dist / GPS_EARTH_RADIUS; // Convert distance to radian
   lon_dif = lon_c - lon_d;
   lon_diflim = 0.0000006399;
   if(lon_dif < lon_diflim && lon_dif > -lon_diflim) //abs
    if(lat_c > lat_d)
      {
         bearing = PI;
      } // end if
      else
      {
       bearing = 0;
      } // end else
   else
   {
      if (sin(lon_d - lon_c) < 0)         // Calculation of bearing
      {
         lat_x = dpFloat2Double(lat_c);
    lat_y = dpFloat2Double(lat_d);
    lon_x = dpFloat2Double(lon_c);
    lon_y = dpFloat2Double(lon_d);
         dista = dpFloat2Double(dist);
         dummy00 = dpDiv(dpSub(dpSine(lat_y),dpMul(dpSine(lat_x),dpCosine(dista))),dpMu
         //bearing = acos(dummy01);
         dummy01 = dpAdd(dpArctan(dpDiv(dpNeg(dummy00),
dpSqrt(dpAdd(dpMul(dpNeg(dummy00),dummy00),dpMakeNum(0x3ff00000,0x0)/*1*/)))),dpMul(dpM
    //dummy01 = dpAtan(-dummy00/dpSqrt(-dummy00*dummy00+1))+2*dpAtan(1)
         bearing = dpDouble2Float(dummy01);
      } // end if
else
      {
```

```
         lat_x = dpFloat2Double(lat_c);
    lat_y = dpFloat2Double(lat_d);
    lon_x = dpFloat2Double(lon_c);
    lon_y = dpFloat2Double(lon_d);
         dista = dpFloat2Double(dist);
         dummy00 = dpDiv(dpSub(dpSine(lat_y),dpMul(dpSine(lat_x),dpCosine(dista))),dpMu
         //bearing = 2*PI-acos((sin(lat_d)-sin(lat_c)*cos(dist))/(sin(dist)*cos(lat_c))
         dummy01 = dpAdd(dpArctan(dpDiv(dpNeg(dummy00),
dpSqrt(dpAdd(dpMul(dpNeg(dummy00),dummy00),dpMakeNum(0x3ff00000,0x0)/*1*/)))),dpMul(dpM
    //dummy01 = dpAtan(-dummy00/dpSqrt(-dummy00*dummy00+1))+2*dpAtan(1)
         bearing = dpDouble2Float(dummy01);
         bearing = 2*PI - bearing;
      } // end else
   } // end else
   return bearing * (180 / PI);
}


/*** BeginHeader gps_basing_point */
gps_basing_point(GPSPosition *c, GPSPosition *bp, float tc1);
extern float dist_bp;
/*** EndHeader */

/* START FUNCTION DESCRIPTION ********************************************
gps_bearing               <gps.lib>

SYNTAX: float gps_bearing(GPSPosition *c, GPSPosition *bp, tc1);

KEYWORDS:      gps

DESCRIPTION:   Calculates lat and lon of a basing_point bp at a certain distance
dbp from starting point c with the initial bearing tc1

PARAMETER1: c - starting point
PARAMETER2: bp - basing_point
PARAMETER3: tc1 in true degrees
RETURN VALUE:

SEE ALSO:

END DESCRIPTION **********************************************************/

gps_basing_point(GPSPosition *c, GPSPosition *bp, float tc1)
{
float lat_c, lon_c, lat_d, lon_d, dist, dummy2;
   int dummy;


lat_c = c->lat_degrees + c->lat_minutes/60;
if(c->lat_direction == 'S')
lat_c = -lat_c;
lat_c = lat_c * PI / 180;
lon_c = c->lon_degrees + c->lon_minutes/60;
  if(c->lon_direction == 'E')
lon_c = -lon_c;
lon_c = lon_c * PI / 180;
```

```
tc1 = tc1 * (PI / 180);
   dist = dist_bp / GPS_EARTH_RADIUS;

   lat_d = asin(sin(lat_c) * cos(dist) + cos(lat_c) * sin(dist) * cos(tc1));
     if (cos(lat_d) == 0)
        lon_d = lon_c;      // endpoint a pole
     else
        lon_d = (lon_c - asin(sin(tc1) * sin(dist) / cos(lat_d)) + PI);
        dummy = (int) ((lon_d) / (2 * PI));
        dummy2 = (float) dummy * (2 * PI);
        lon_d = lon_d - dummy2;
        lon_d = lon_d - PI;

    lat_d = lat_d * 180 / PI;
    if(lat_d < 0)
     bp->lat_direction = 'S';
    else bp->lat_direction = 'N';
    dummy = (int) lat_d;
    bp->lat_degrees = dummy;
    lat_d = (lat_d - (float)dummy) * 60;
    bp->lat_minutes = lat_d;


    lon_d = lon_d * 180 / PI;
    if(lon_d < 0)
     bp->lon_direction = 'E';
    else bp->lon_direction = 'W';
 dummy = (int) lon_d;
    bp->lon_degrees = dummy;
    lon_d = (lon_d - (float)dummy) * 60;
    bp->lon_minutes = lon_d;


}


/*** BeginHeader getgps */
char *getgps(char *buffer_gps);
/*** EndHeader */

/* START FUNCTION DESCRIPTION ****************************************
getgps(*in_str)               <gps.lib>

SYNTAX: char getgps(*in_str);

KEYWORDS:      gps

DESCRIPTION:   gets gps data string from serC

PARAMETER1:    string to put

RETURN VALUE:  string from modem

SEE ALSO:
```

```
END DESCRIPTION **********************************************************/


char *getgps(char *buffer_gps)
{

auto int i,ch,m;
   serCwrFlush();
   serCrdFlush();
memset(buffer_gps, 0x00, sizeof(buffer_gps));

i = 0;
m = 0;

WrPortI ( PBDDR, &PBDDRShadow, 0xFF );   // PB = all output

SPIinit();

while((ch = serCgetc()) != '\n' )
{ // start while
    // Copy only valid RCV'd characters to the buffer
   if(ch != -1)
   {
    buffer_gps[i++] = ch;
   } // endif
   }   //end while

buffer_gps[i++] = ch;      //copy '\r' to the data buffer
buffer_gps[i]   = '\0';     //terminate the ascii string


return buffer_gps;
} // end getstring



/*** BeginHeader */
#endif
/*** EndHeader */
```

D.4 navigate.lib

```
/*** BeginHeader */
#ifndef __NAVIGATE_LIB
#define __NAVIGATE_LIB
#use gps.lib
#use drive.lib
/*** EndHeader */


/* START LIBRARY DESCRIPTION ********************************************
21mar2005
navigate.lib
Goetz Dietrich, 2005
-changed routine for having invalid string
- stops after (wp_count+1)th waypoint and manual drive mode
- sends back cp[2]
- changed startup !!!

navigate
turn_full
turn_partial


END DESCRIPTION **********************************************************/



/*** BeginHeader navigate */

int navigate(char *in_strie);
extern GPSPosition start_p;
extern GPSPosition curr_p1;
extern GPSPosition curr_p2;
extern GPSPosition active_wp;
extern GPSPosition last_wp;
extern GPSPosition basing_p;
extern GPSPosition wp_list[100];
extern float initial_dist;
extern float dist_to_wp;
extern float dist_to_basep;
extern float curr_dist;
extern float initial_bearing;
extern float bearing_to_wp;
extern float bearing_to_bp;
extern float curr_bearing;
extern float off_bearing;
extern float off_track;
extern float alpha;             // used for the off_track calculation
extern int wp_active;
extern int motor_speed[4];
extern char key_input;
extern char out_string[256];
extern char in_stri;
```

```
extern int send_event;
extern int wp_start;
extern int wp_count;
extern int dist_bpdiv;
extern int GPS_inv_limit;
//extern File logfile;

/*** EndHeader */

GPSPosition start_p;
GPSPosition curr_p1;
//GPSPosition curr_p2;
GPSPosition active_wp;
GPSPosition last_wp;
GPSPosition basing_p;
float initial_dist;
float dist_to_wp;
float dist_to_basep;
float curr_dist;
float initial_bearing;
float bearing_to_wp;
float bearing_to_bp;
float curr_bearing;
float off_bearing;
float off_track;
float alpha;            // used for the off_track calculation
float dist_bp;
int dist_bpdiv;



/* START FUNCTION DESCRIPTION ************************************************
navigate() <navigate.lib>

SYNTAX:  void navigate();

DESCRIPTION:   basic navigation needs for CRobot to head to the next waypoint

PARAMETER1:  active_wp  is position of waypoint in array "waypoints"

RETURN VALUE:   0 - GPS parsing error
 1 - sentence marked invalid
                2 - correct function
                3 - reached last waypoint

KEY WORDS:

END DESCRIPTION ***************************************/

int navigate(char *in_strie)
{

int count_invalid, turn_lim;
   float wp_range;
   float bp_range;
   count_invalid = 0;
```

```
   wp_range = 0.030;
   bp_range = 0.045;
   turn_lim = 90;
      while(count_invalid != GPS_inv_limit)
{
costate
    {
    waitfor(DelayMs(1000));
       count_invalid++;
       getgps(in_strie);
            if(gps_get_position(&curr_p1, in_strie) == 0)
   {
                   break;
                  }
            if (gps_get_position(&curr_p1, in_strie) == -1)
            {
       sprintf(out_string,"GPS parsing error\n\r");
       send_event = 5;

       } // end if
       if (gps_get_position(&curr_p1, in_strie) == -2)
       {
       sprintf(out_string,"GPS sentence invalid\n\r");
       send_event = 5;

       } // end else if
       if(count_invalid == GPS_inv_limit)
       {
       drive_mode = 5;
               return 0;
       } // end if
    } // end costate
} // end while
      if (gps_get_position(&curr_p1, in_strie) == 0);
      {
active_wp = wp_list[wp_active];
         if(wp_start == 0)           // only once! at startup
         {
            //curr_p2 = curr_p1;
            initial_dist = gps_ground_distance(&curr_p1, &active_wp);
            initial_bearing = gps_bearing(&curr_p1, &active_wp, initial_dist);
            dist_bpdiv = initial_dist/dis_bp;
            dist_bp = initial_dist/dist_bpdiv;
            gps_basing_point(&curr_p1, &basing_p, initial_bearing);
            wp_start++;
         } // end if
         dist_to_wp = gps_ground_distance(&curr_p1, &active_wp);
         bearing_to_wp = gps_bearing(&curr_p1, & active_wp, dist_to_wp);
         dist_to_basep = gps_ground_distance(&curr_p1, &basing_p);
         bearing_to_bp = gps_bearing(&curr_p1, &basing_p, dist_to_basep);
         curr_dist = gps_ground_distance(&curr_p2, &curr_p1);
         curr_bearing = gps_bearing(&curr_p2, &curr_p1, curr_dist);

        sprintf(out_string,"aw:%d%f,%c,%d%f,%c:bp:%d%f,%c,%d%f,
        %c:cp1:%d%f,%c,%d%f,%c:cp2:%d%f,%c,%d%f,%c:dw:%f:bw:%f
        :dbp:%f:bbp:%f:cd:%f:cb:%f\n\r",
```

```
            active_wp.lat_degrees, active_wp.lat_minutes,
  active_wp.lat_direction, active_wp.lon_degrees,
            active_wp.lon_minutes, active_wp.lon_direction,
     basing_p.lat_degrees, basing_p.lat_minutes,
  basing_p.lat_direction, basing_p.lon_degrees,
            basing_p.lon_minutes, basing_p.lon_direction,
            curr_p1.lat_degrees, curr_p1.lat_minutes,
            curr_p1.lat_direction, curr_p1.lon_degrees,
            curr_p1.lon_minutes, curr_p1.lon_direction,
            curr_p2.lat_degrees, curr_p2.lat_minutes,
            curr_p2.lat_direction, curr_p2.lon_degrees,
            curr_p2.lon_minutes, curr_p2.lon_direction,
            dist_to_wp, bearing_to_wp,
            dist_to_basep, bearing_to_bp,
            curr_dist, curr_bearing);
// fopen_wr(&logfile,LOG_FILE_NAME);
// fwrite(&logfile,out_string,strlen(out_string));
// fclose(&logfile);
// printf("%s\n",out_string);
 send_event = 5;

 if (dist_to_wp <= wp_range)
 {
  wp_active ++;
    if(wp_active == wp_count+1)                  // stops crobot last waypoint
    {
     //stop(motor_speed, motor_speed_increment);
       drive_mode = 5;
       return 2;
    } // end if
   last_wp = wp_list[wp_active-1]; // store last waypoint
  active_wp = wp_list[wp_active]; // update waypoint

    initial_dist = gps_ground_distance(&last_wp, &active_wp);
    initial_bearing = gps_bearing(&last_wp, &active_wp, initial_dist);
    dist_to_wp = gps_ground_distance(&curr_p1, &active_wp);
    bearing_to_wp = gps_bearing(&curr_p1, & active_wp, dist_to_wp);
    dist_bpdiv = initial_dist/dis_bp;
    dist_bp = initial_dist/dist_bpdiv;
    gps_basing_point(&last_wp, &basing_p, initial_bearing);

    dist_to_basep = gps_ground_distance(&curr_p1, &basing_p);
    bearing_to_bp = gps_bearing(&curr_p1, &basing_p, dist_to_basep);
 } // end if
 else
 {

    if ( dist_to_basep <= bp_range)
    {
     if(dist_to_wp > 2*dist_to_basep)
       {
     gps_basing_point(&basing_p, &basing_p, initial_bearing);
        dist_to_basep = gps_ground_distance(&curr_p1, &basing_p);
        bearing_to_bp = gps_bearing(&curr_p1, &basing_p, dist_to_basep);
       } // end if
    } // end if
```

```
         } // end else

         // calculation of the track offset
         if ( bearing_to_bp > initial_bearing)
         {
          alpha = bearing_to_bp - initial_bearing;
         } // end if
         else
         {
          alpha = initial_bearing - bearing_to_bp;
         } // end else
alpha = alpha * PI / 180;
         off_track = sin(alpha) * dist_to_basep;

         if (dist_to_wp <= 1.5*dist_to_basep)
         {
          off_bearing = bearing_to_wp - curr_bearing;
         } // end if
         else
         {
          off_bearing = bearing_to_bp - curr_bearing;
         } // end else
         if(off_bearing > 180)
    {
    off_bearing = off_bearing -360;
    } // end if
    if(off_bearing < -180)
    {
    off_bearing = off_bearing + 360;
    } // end if
    if(off_bearing < -turn_lim)
    {
    off_bearing = -turn_lim;
    } // end if
    if(off_bearing > turn_lim)
    {
    off_bearing = turn_lim;
    } // end if
         //printf("gps string is: %s\n", in_strie);            // only for use with nav
         curr_p2 = curr_p1; // store two points with x sec difference for navigation
         printf("off bearing is %f\n", off_bearing);
         if ( off_bearing >= 4 || off_bearing <= -4|| off_track >= 20)
         {
          if(drive_mode == 1)
            {
            turn_full(off_bearing); // function that makes z degree turn??!
            } // end if
            if (drive_mode == 2)
            {
             turn_partial(off_bearing); // function to make z degree turn at 60% speed
            } // end if
            getgps(in_strie);
            while(count_invalid != GPS_inv_limit)
{
costate
    {
```

```
    waitfor(DelayMs(1000));
       count_invalid++;
       getgps(in_strie);
                  if(gps_get_position(&curr_p2, in_strie) == 0)
   {
                   break;
                  }
                  if (gps_get_position(&curr_p2, in_strie) == -1)
       {
       sprintf(out_string,"GPS parsing error\n\r");
       send_event = 5;

       } // end if
       if (gps_get_position(&curr_p2, in_strie) == -2)
       {
       sprintf(out_string,"GPS sentence invalid\n\r");
       send_event = 5;

       } // end else if
       if(count_invalid == GPS_inv_limit)
       {
                     drive_mode = 5;
                     return 0;
       } // end if
    } // end costate
} // end while
         } // end if
      } // end else if
      return 2;
} // end function


/*** BeginHeader turn_full */
void turn_full(float off_bearing);
#use analogin.lib
/*** EndHeader */

/* START FUNCTION DESCRIPTION ************************************************
turn_full(off_bearing) <navigate.lib>

SYNTAX:  void turn_full(float off_bearing);

DESCRIPTION:   makes a turn of (off_bearing) degrees to right(off_bearing > 0)
or left(off_bearing < 0)

PARAMETER1:  calculated off_bearing from initial course to waypoint

RETURN VALUE:   None

KEY WORDS:

END DESCRIPTION ***********************************************/



void turn_full(float off_bearing)
```

```
{
auto int i;
   long turning_tm;
   i = 1;

   if(off_bearing <= 0)
   {
turning_tm = (int)off_bearing*(-300);
      motor_speed[2] = 90;         // motor speeds are set to 100 !!
      motor_speed[1] = 90;
      UpdateMotorOutput();
      while(i == 1)
      {
         costate
         {
          waitfor (DelayMs(1000));
            read_sensors();                    // interrupts??? !!!
         }       // end costate
         costate
         {
          waitfor (DelayMs(turning_tm));
            motor_speed[2] = 100;
       motor_speed[1] = 100;
       UpdateMotorOutput();
            i = 0;
         } // end costate
      } // end while
   } // end if
else if(off_bearing > 0)
   {
    turning_tm = (int)off_bearing*300;
    motor_speed[0] = 88;         // motor speeds are set to 100 !!
      motor_speed[3] = 88;
      UpdateMotorOutput();
      while(i == 1)
      {
         costate
         {
          waitfor (DelayMs(1000));
            read_sensors();
         }       // end costate
         costate
         {
          waitfor (DelayMs(turning_tm));
            motor_speed[0] = 100;
       motor_speed[3] = 100;
       UpdateMotorOutput();
            i = 0;
         } // end costate
      } // end while

   } // end else if
} // end function

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader turn_partial */
```

```
void turn_partial(float off_bearing);
#use analogin.lib
/*** EndHeader */

/* START FUNCTION DESCRIPTION ********************************************
turn_partial(off_bearing) <navigate.lib>

SYNTAX:  void turn_partial(float off_bearing);

DESCRIPTION:   makes a turn of (off_bearing) degrees to right(off_bearing > 0)
or left(off_bearing < 0)

PARAMETER1:  calculated off_bearing from initial course to waypoint

RETURN VALUE:   None

KEY WORDS:

END DESCRIPTION **************************************/



void turn_partial(float off_bearing)
{
auto int i;
   long turning_tm;
   i = 1;

   if(off_bearing <= 0)
   {
turning_tm = (int)off_bearing*(-300);
      motor_speed[0] = 45;         // motor speeds are set to 100 !!
      motor_speed[1] = 45;
      UpdateMotorOutput();
      while(i == 1)
      {
         costate
         {
          waitfor (DelayMs(1000));
            read_sensors();
         }       // end costate
         costate
         {
          waitfor (DelayMs(turning_tm));
            motor_speed[0] = 60;
       motor_speed[1] = 60;
       UpdateMotorOutput();
            i = 0;
         } // end costate
      } // end while
   } // end if
else if(off_bearing > 0)
   {
    turning_tm = (int)off_bearing*300;
    motor_speed[2] = 44;         // motor speeds are set to 100 !!
      motor_speed[3] = 44;
```

```
      UpdateMotorOutput();
      while(i == 1)
      {
         costate
         {
          waitfor (DelayMs(1000));
            read_sensors();
         }       // end costate
         costate
         {
          waitfor (DelayMs(turning_tm));
            motor_speed[2] = 60;
       motor_speed[3] = 60;
       UpdateMotorOutput();
            i = 0;
         } // end costate
      } // end while

   } // end else if
} // end function


/*** BeginHeader */
#endif
/*** EndHeader */
```

D.5 radiocomm_e.lib

```
/* Toni Zettl March 15th 2005 */

/*** BeginHeader */
#use GPS.LIB
/*** EndHeader */

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader str2wayp */
int str2wayp(char *in_str, GPSPosition *wayp);
extern int wp_count;
extern GPSPosition wp_list[100];
/*** EndHeader */
/* START FUNCTION DESCRIPTION ****************************
termStr <radiocomm_e.lib>

SYNTAX:        int str2wayp(char *in_str);

DESCRIPTION:   This function converts a string to datastructure GPSPosition and
and place the waypoint(s) within the string in the global
               variable wp_list.

PARAMETER1: Pointer to string up to 255 characters long

RETURN VALUE:  integer with number of waypoints successful written to wp_list.
0 if an error occured.

KEY WORDS: string, waypoint, GPSPosition, convert

END DESCRIPTION ****************************************/


int str2wayp(char *in_str, GPSPosition *wayp)
{
  int wp_number,i,written_wp;
   //GPSPosition wp_list[100];
   char buff[256];

   //printf("%s\n",in_str);
   in_str = strchr(in_str,',')+1; // pointer locatet to first char after first ","

   memcpy(buff,in_str,1); // get number of waypoints
   buff[1] = '\0';
   wp_number = atoi(buff);
   for(i=0;i<wp_number;i++)
   {
    in_str = strchr(in_str,',')+1; // pointer to first char of waypoint
//printf("%s\n",in_str);

      memcpy(buff,in_str,12); // copy lat_ddmm.ssss to buff
   buff[12] = '\0';        // terminated buff with NULL
   if(gps_parse_coordinate(buff,&wayp->lat_degrees,&wayp->lat_minutes) == -1)
      {
       return i;
```

```
      }
   memcpy(buff,in_str+10,10); // copy lon_dddmm.ssss to buff
   buff[10] = '\0';           // terminate buff with NULL
   if(gps_parse_coordinate(buff,&wayp->lon_degrees,&wayp->lon_minutes) == -1)
         {
       return i;
      }
   in_str = in_str+9;              // pointer to lat_direction
      if((strncmp(in_str,"N",1) == 0) || (strncmp(in_str,"S",1) == 0))
      {
    wayp->lat_direction = *in_str;  // write lat_direction to wayp
      }
      else
      {
       return i;
      }
   in_str = in_str+11;             // pointer to lon_direction
      if((strncmp(in_str,"W",1) == 0) || (strncmp(in_str,"E",1) == 0))
      {
   wayp->lon_direction = *in_str;  // write lon_direction to wayp
      }
      else
      {
       return i;
      }
      wp_list[wp_count] = *wayp; // write wayp to wp_list
   wp_count++;                // increment wp_count
   } // end for
   return i;
} // end str2wayp

////////////////////////////////////////////////////////////////////////////
/*** BeginHeader termStr */
char *termStr(char *buffer);
extern char buffer[256];
/*** EndHeader */
int m;
/* START FUNCTION DESCRIPTION ****************************
termStr <radiocomm_e.lib>

SYNTAX:  char *termStr(char *buffer);

DESCRIPTION:   The function simply terminates a string pointed to by buffer with
               a carriage return '\r'. Buffer points to the terminated string
afterwards.

PARAMETER1: Pointer to string up to 255 characters long

RETURN VALUE:  Pointer to the carriage return terminated string

KEY WORDS: carriage return; terminate

END DESCRIPTION ***************************************/


char *termStr(char *buffer)
```

```
{
int m;
m = 0;
while(buffer[m] != '\0')
{
buffer[m] = buffer[m];
m++;
}
buffer[m++] = '\r';
buffer[m] = '\0';
return buffer;
} // end termStr


////////////////////////////////////////////////////////////////////////////
/*** BeginHeader clearStr */
char *clearStr(char *str);
/*** EndHeader */
/* START FUNCTION DESCRIPTION ******************************
clearStr <radiocomm_e.lib>

SYNTAX:  void *clearStr(char *buffer);

DESCRIPTION:   Function deletes leading line feeds ('\n') and "cmd:"-strings
the string pointed to by buffer.

PARAMETER1: Pointer to string up to 255 characters long

RETURN VALUE:  none

KEY WORDS: clear, line feed, string

END DESCRIPTION **************************************/


char *clearStr(char *str)
{
   char dummy[256];
   memset(dummy, 0x00, sizeof(dummy));
   while(1)
   {
    if(str[0] == '\n')
      {
       //str++;
       memcpy(dummy,str+1,254);
         memcpy(str,dummy,sizeof(dummy));
      } // end if
      else if(strncmp(str,"cmd:",4) == 0)
      {
       //str += 4;
       memcpy(dummy,str+4,250);
         memcpy(str,dummy,sizeof(dummy));
      }
      else
      {
       return str;
```

```
      }
   } // end while
} // end clearStr


////////////////////////////////////////////////////////////////////////////
/*** BeginHeader processModemStr */
int processModemStr(char *chk_string);
extern int status_modem;
extern int wp_rcvd;
extern int send_event;
extern int tm_count;
extern char in_string[256];
/*** EndHeader */
static const char cmp_connected[] = "*** CONNECTED to GOEK";
static const char cmp_modemon[] = "DUPLICATION PROHIBITED";
static const char cmp_disconnected[] = "*** DISCONNECTED";
static const char cmp_setbaud[] = "PRESS (*) TO SET BAUDRATE";
static const char cmp_modemtest2[] = "EH?";
static const char cmp_modemtest1[] = "cmd:   $";
/* START FUNCTION DESCRIPTION ****************************
processModemStr <radiocomm_e.lib>

SYNTAX:  int processModemStr(char *chk_string);

DESCRIPTION:

PARAMETER1: Pointer to string up to 255 characters long

RETURN VALUE:  Integer value 0, 1 or 2 for status of the modem

KEY WORDS:

END DESCRIPTION ****************************************/


int processModemStr(char *chk_string)
{
   char in_string[256];
   int str_len;
   int k;
   GPSPosition wayp;

   clearStr(chk_string);  // deletes leading '\n' and "cmd:" from the input string

   if(strlen(chk_string) == 0)
{
return 0;
}
   // detects if a connection is established
if(strncmp(chk_string,cmp_connected,15) == 0)
{
   status_modem = 2;
      printf("connected\n");
      return 2;
}
```

```
   // detect if the modem is on
else if(strncmp(chk_string,cmp_modemon,10) == 0
|| strncmp(chk_string,cmp_modemtest1,5) == 0
|| strncmp(chk_string,cmp_modemtest2,3) == 0)
{
status_modem = 1;
      tm_count = 0;
      printf("modem on\n");
return 1;
   } // end else if
   // detects a disconnection
   else if(strncmp(chk_string,cmp_disconnected,15) == 0)
   {
      //printf("\n***** DiScOnNeCtEd *****\n");
      while(motor_speed[0] != 0 || motor_speed[3] != 0
      || motor_speed[1] != 0 || motor_speed[2] != 0)
     {
     stop(motor_speed, motor_speed_increment);
     } // end while
      drive_mode = 5;
      status_modem = 1;
      return 1;
   }
   else //if(status_modem == 2) // no modem_cmd ...
   {
      if(strncmp(chk_string, "$CRWPT", 6) == 0) // case2: waypoint(s) recieved
      {
         str_len = strlen(chk_string);
         memcpy(in_string,chk_string,str_len+1);
         wp_rcvd = str2wayp(in_string,&wayp);
         if(wp_rcvd != -1)   // no error while storing WPs
         {
            send_event = 1; // send number of waypoints succesfully received
         }
         return 4;
      } // end if
      else if(strncmp(chk_string, "$CRCMD", 6) == 0) // case3: command recieved
      {
       if(strncmp((chk_string+6), "MANDM", 5) == 0)  // cmd for entering
         { // manual drive mode
          drive_mode = 5;         // switch to maunal drive mode
  stop(motor_speed, motor_speed_increment);
memset(in_string, 0x00, sizeof(in_string));
         }
         else if(strncmp((chk_string+6), "WPFFL", 5) == 0)  // cmd for entering
         { // waypoint following full speed
          drive_mode = 1;         // switch to wp_follow_full
  stop(motor_speed, motor_speed_increment);
memset(in_string, 0x00, sizeof(in_string));
         }
         else if(strncmp((chk_string+6), "WPFPT", 5) == 0)  // cmd for entering
         { // waypoint following partial speed
          drive_mode = 2;         // switch to wp_follow_partial
  stop(motor_speed, motor_speed_increment);
memset(in_string, 0x00, sizeof(in_string));
         }
```

```
         else if(strncmp((chk_string+6), "GOTST", 5) == 0)  // cmd for entering
         { // got stuck mode
          drive_mode = 3;         // switch to got_stuck
  stop(motor_speed, motor_speed_increment);
memset(in_string, 0x00, sizeof(in_string));
         }
       return 5;
      }
      else if(strncmp(chk_string, "$CRSRQ", 6) == 0)  // case4: status request
      {
         send_event = 3;  // send back a status report
       return 6;
      }
      else if(strncmp(chk_string, "$CRDRQ", 6) == 0)  // case5: data request
    {
       send_event = 4;  // send back last ...mins of data stored
       return 7;
      } // end elseif
      else  // case6: undefined/unimportend
      { // string received
       return 8;
      }
   } // end if
}// end processModemStr
```

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