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MASTER'S THESIS

Tether Tracking and Control of ROSA Robotic Rover

Jamshed Iqbal

Luleå University of Technology

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HELSINKI UNIVERSITY OF TECHNOLOGY
Department of Automation and Systems Technology

LULEÅ UNIVERSITY OF TECHNOLOGY

Jamshed Iqbal

Tether Tracking and Control of ROSA Robotic Rover

Thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Technology

Espoo, 26.07.2007

Supervisors:

Professor Aarne Halme	Professor Kalevi Hyyppä
Helsinki University of Technology	Luleå University of Technology

Instructor:

Seppo Heikkilä
Helsinki University of Technology

Preface

Infinite praise definitely goes to God Almighty, Who has given me strengths to accept and achieve this challenging task.

I wish to thank my thesis supervisors, Professor Aarne Halme and Professor Kalevi Hyyppä for their expert comments and kind guidance. I would really like to thank my instructor Seppo Heikkilä for his kind support and time through out thesis during thesis planning, scheduling, prototyping, designing, implementing, debugging, testing, analyzing and documentation phases of project. I am grateful to Mr. Tomi Ylikorpi for reading first two chapters of thesis and giving very useful feedback. Thanks to my friend Mr. Abdul Rahim for his kind help in making thesis diagrams. Last but not the least, warm thanks go to my dearest sister Imaan Fatima for her greatest support and patience for ever.

Jamshed Iqbal
Otaniemi, July 26, 2007

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ABSTRACT OF THE MASTER'S THESIS

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Mars is currently centre of interest for space exploration. Tremendous efforts are still in progress to find clues of existence of life on Mars. Rovers are major sources of information of Mars. This thesis focuses on a robotic roving vehicle ROSA having its initiative of ESA. The 1st part of thesis aims to test mobility system and to develop tether motors control strategy of ROSA. The rover should be capable of executing motion commands communicated from ground station. ROSA being a tethered rover provides additional advantages. Power is delivered to the rover through the tether. This gives possibility to reduce the weight/size of rover. The tether also provides communication lines between lander and rover. A tethered robot requires a complex control system. The 2nd part of the thesis consists of developing a specialized tracking system for rover's 40 m tether. The developed system is capable of tracking within resolution of ±6 cm and can also be used in other tethered robots for rescue, security, underwater, autonomous vehicles, mines hunting and cleaning petroleum tanks.

Keywords: Robotic Vehicle, ROSA, Mars exploration

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Symbols and Abbreviations

ASTs	Above-ground Storage Tanks
AUV	Autonomous Underwater Vehicle
C^3U	Central Command & Control Unit
CCD	Charged Couple Device
DCHH	Data & Control Handling Hardware
DSS	Drilling and Sampling Subsystem
ESA	European Space Agency
GPS	Global Positioning System
LAN	Local Area Network
LARS	Launch and Recovery System
LED	Light Emitting Diode
NASA	National Aeronautics and Space Administration
OBC	On Board Computer
PLC	Pay Load Cab
ROSA	Robot for Scientific Applications
ROV	Remotely Operated Vehicle
SS	Sub System
TM	Tether Management
TUI	Tether's Unlimited Inc.
WTC	World Trade Centre

Foreword

This thesis rests on and continues author's work performed in Laboratory of Automation and Systems of Helsinki University of Technology, Finland

Chapter 1

Introduction

This thesis is related to the ROSA rover. The operational scenario includes sending a lander to Mars. During the voyage, the rover is fixed inside one of the petals of the lander. After landing these petals are opened and the sample collection can begin. The rover is teleoperated and it operates in the close vicinity of the lander. Navigating by the lander camera, rover moves to the selected target and performs drilling in automatic way. The collected samples are of two basic types: samples extracted from surface rocks at depth of a few centimeters and deep soil samples acquired vertically from a depth of more than one meter. After sampling, the rover follows the tether to return back to the lander. Hence ROSA delivers the collected samples to the lander, where the samples are analyzed. The objective of this thesis is to propose and implement a specialized control system for the ROSA tether. As per given requirements, system may be based on vision, ultrasound, whiskers or other measuring methods.

The contents of the thesis are arranged so that Chapter 1 gives an overview of the Martian environment. It gives a motivation for searching life on Mars followed by brief past and future exploration missions. Chapter 2 presents a detailed literature survey of tethered based applications for space, underwater and terrestrial applications. Chapter 3 discusses tether tracking systems based on vision, proximity and tactile sensors. It also introduces merits and demerits of each system. Chapter 4 introduces ROSA background and its subsystems details related to thesis. Chapter 5 gives implementation details covering both parts of the thesis: mobility system and tether control. Electronic, mechanic and software side of proposed hardwares have been presented in detail. Chapter 6 discusses the results. Suggestions to improve the system have been proposed. The last chapter also summarizes the project and discusses future development.

1.1 Mars

Mars is the fourth planet from the sun, and is the outermost of the terrestrial planets. It is the second closest planet to the Earth. The mass of Mars is $0.64*10^{24}$ kg, which is about 11 percents of the mass of the Earth. With a diameter of 6788 kilometers, Mars is about half the size of the Earth. Due to its elliptical orbit, thin atmosphere and lack of ocean Mars has an extraordinary wide range of surface temperatures. Since, the Mars has no oceans, so this makes the land area of Mars equal to the land area of the Earth. Mars is coated with iron oxide minerals and therefore appears reddish. Since the mass of Mars is only 11 percents of the mass of the Earth, Mars loses its internal heat much faster. This fact has made the geologic history of Mars much simpler than the one of the Earth.

Mars has been named after the Roman god of war (Ares in Greek history), and the planet was probably given this name because of its red color, resembling blood in the battlefields. Therefore Mars is frequently referred to as the Red Planet. Now we know that the red color is caused by rust (iron oxide) on the surface. An image of the planet is seen in figure 1.1, which has been taken by the Hubble Space Telescope in August 2003 (Mars opposition). Surface view of Mars can also be seen in the figure, which is taken by the Mars Exploration Rover Spirit in March 2004.

Fig. 1.1 The Mars [Bell, 2003] (left) and Mars surface view (right) [NASA, 2004a]

Mars has an atmosphere but it is quite different from that of Earth. The main constituent is carbon dioxide, with only small amounts of other gases, such as nitrogen, argon and oxygen. Table 1.1 summarizes the characteristics of Mars in numerical form.

Table 1.1 Mars-An overview [NASA, 1995]

Orbital		Physical		Atmospheric	
Semi-major axis	227936637 km	Equatorial radius	3402.5 km	Surface pressure	0.7–0.9 kPa
Sidereal period	1.8808 yr	Polar radius	3377.4 km	CO_2	95.72%
Eccentricity	0.09341233	Oblateness	0.007 36	N_2	2.7%
Orbital speed	24.077 km/s	Gravity	0.376g	Ar	1.6%
Satellites	2	V_{escape}	5.027 km/s	O_2	0.2%
Inclination	1.850 61°	Volume	1.6×1011 km³	H_2O vapor	0.03%

1.2 Mars exploration – Motivation

Mars is the primary place to study in a detailed manner, because it is the most Earth-like planet in our Solar System. Recent measurements show the presence of water [NASA, 2007a] which raises the likelihood of finding traces of extinct life. Figure 1.2 shows microscopic rock forms indicating past signs of water, taken by Opportunity. In addition, Mars is also the most hospitable celestial body for humans to visit. Although the Moon is much closer than Mars, the latter offers far better conditions for astronauts to explore the surface due to the day length, greater gravity and radiation protection. Even Venus is closer than Mars, but runaway greenhouse effect has developed a very dense carbon dioxide atmosphere. This, in turn, has resulted in the escape of all of its possibly existed water and created an infernal surface temperature of nearly 500 °C [Anttila, 2004].

Fig. 1.2 Signs of Water on Mars [NASA, 2004b]

Exploring Mars will enhance our knowledge of the Solar System's history and formation of the planets. In case Mars has watery past, there are high chances that it has also hosted life in its history. If traces of extinct life could be found, that would naturally raise some fundamental questions and change the way that the humankind thinks of the life itself.

Even though it is said that one competent field geologist could achieve the same results in one day that a robot could do in its whole lifetime, it is not always feasible to send astronauts instead of robotic explorers. Before the astronauts can be sent to the Red Planet, a thorough research is to be done in several science areas. The Exobiology Program Office of NASA has divided the scientific issues involved in the exobiological exploration of Mars into three general categories [NASA, 1995]:

1. To what extent did periodic chemical evolution proceed on Mars?
2. If chemical evolution occurred, did it lead to synthesis of replicating molecules i.e., life, which subsequently became extinct?
3. If replicating systems arose on Mars do they persist anywhere on Mars today?

1.3 Mars exploration – Past & future

The search for life on Mars can be studied from several standpoints. These standpoints are based on assumptions and the available information about the Martian environment. The main focus in the current research is on finding out which, if any, standpoints can be proved to be right. In the exobiological strategy report NASA introduces research phases that can be applied regardless of the standpoint.

The **first phase** involves orbital research to find out if assumed conditions really exist on Mars. Also locating the most promising areas is involved.

The **second phase** involves landed mission providing in situ descriptions of sites selected in the previous phase. This phase is to give more detailed information about the environmental conditions.

The **third phase** is also so called landed mission. This time the focus is on finding the evidence of life. This is the last phase that has so far been implemented.

The **fourth phase** is still far in the future. It involves sample return from Mars. This phase is required, since the best scientific equipment can never be brought to Mars. If the earlier phases give encouraging results, this phase is to perform more detailed experiments.

The **fifth phase** includes human mission to Mars. This phase is justified by the fact that human can always perform more intelligent sampling than machine. For example, the sampling site can more easily be selected if a man is on Mars and no teleoperation is needed.

Although still in future, the last phases need a lot of research before they can be performed. Especially the contamination of Martian and terrestrial factors must be studied. Since we do not know what kind of organism exists on Mars, we are not aware of the way they could react with terrestrial organisms. The challenge of the missions have mostly been getting there; only roughly one third of all Mars missions have reached their goal, either an orbit around the planet, or landing to the surface. The two Viking landers in the 1970's were the first to touch down on the soil of Mars in working order and performing scientific studies there. After that there was a long gap, until 1997 the Pathfinder landed safely on the surface and released a little rover, the Sojourner. In 2004 other rovers came: the Mars Exploration Rover Spirit and a while after that, the sister rover Opportunity. These five successful landings are less than half of all attempts to land on Mars. Russia, Europe and the United States have all had their landers, but Mars is challenging. Figures 1.3 shows examples of fly by, orbiter and rovers for Mars exploration.

Future plans for unmanned Mars Exploration include the sending of the Phoenix Lander in 2007, followed by the Mars Science Laboratory in 2009, the Phobos-Grunt sample-return mission, to return samples of Phobos, a Martian moon. Other missions have been proposed, although not yet confirmed. ESA hopes to land the first humans on Mars between 2030 and 2035. This will be preceded by successively larger probes, starting with the launch of the ExoMars probe in 2013, followed by the 'Mars Sample Return Mission'. Likewise, astronauts will be sent to the moon between 2020 and 2025 in preparation for this mission.

Fig. 1.3 Earth Mars flyby (left), Mars orbiter (centre) and Mars lander (right) [NASA]

Chapter 2

Background study

A **tether** is a cord that anchors something, such as an animal, to something else, such as a pole. This term is sometimes used to describe using the Internet through a cell phone via a cable or Bluetooth. The tether can be as simple as a rope or chain for tethering animals and as sophisticated as cabling for under-water submersibles which provides air, power and communication links with the surface. In robotics, the word tethered robot system generally has been used for describing mobile robots restricted by power supply and/or data communication cabling [Edwardo, 2000]. On the other hand, the word **untethered** has been mostly used for autonomous mobile robots with onboard controllers and power source.

A fundamental tool of tethering for many practical applications is a winch system for reeling in/out the tether. Tethering systems typically consist of the tether and components that stack the tether and winding/unwinding the tether. In addition to support, the tether can act as a mean for any subset of the following:

- Power delivery.
- Data communication between remote computer or human controllers and the tethered system.
- Gases such as oxygen supplied to a submersible from a surface ship.
- Fluids such as hydraulic fluid or cleaning fluid for inspection and repair systems.
- Other materials such as debris from a vacuuming robot.

Tethers have been used for a long time in many areas including ground, under-water and aero-space environments. Over the last decade, mobile robot systems have demonstrated the ability to operate in severe environments and perform hazardous tasks. A number of these tasks require tethered robot systems. Tethers have been used for helping robot locomotion on steep slopes. Some other recent studies on cable crane robots**,** autonomous cable winding and unwinding, space robots, rope interfaces, casting manipulators, cable driven robots and path planning also used tethers to some extent.

Although a lot of applications using tethers have been encountered but not much data of their control has been found. This chapter is dedicated to literature survey of different applications using tethers. Tethered robots for rescue operations, in underwater systems, in space and other terrestrial applications have been discussed. Finally a brief note on non-robotic tethered based applications has been presented.

2.1 Rescue robotics

A long standing goal of mobile robotics has been to allow robots to work in environments unreachable or too hazardous to risk human lives. Urban search and rescue is one of the most hazardous environments imaginable. Victims are often in unreachable locations buried beneath rubble. Rescue robotics is the application of robotics to the search and rescue domain. The goal of rescue robotics is to extend the capabilities of human rescuers while also increasing their safety. Rescue robots were used at the WTC disaster, on Sept. 11, 2001. In the chaotic environment of the collapsed towers, radio controlled and tethered robots were deployed eight times. During the course of their deployment the robots encountered a number of difficulties involving radio transmission inefficiency**,** poor maneuverability and tether management [Casper, 2002]. The problem of using radio frequencies at tragedy sites has been raised in these rescue operations. It became evident when a communication failure caused temporary loss of an untethered teleoperated robot. Usable frequencies are limited since most are reserved by emergency response agencies. Additionally, the thick wall of wreckage often hindered radio communication between the operator and the robot. These issues make point-to-point navigation of the smaller tethered robots more reliable and useful than that of the untethered robots. Tethers improve mobility since robots can be safely lowered or raised vertically whereas the untethered robots can not. The problem of using tethers is increased drag and a tendency to catch on obstacles. What is needed is a tether design that actively prevents or solves entanglement problems thus providing more mobility and range for the rescue robots at a reasonable price. Perrin, Albert & Robert proposed a novel actuated tether design for rescue robots using hydraulic transients. For this design, the motion along the tether is created by arresting the flow of water in the tether. By inducing movement along the tether it can be freed if caught. This motion also reduces the overall likelihood of the tether becoming caught in the first place.

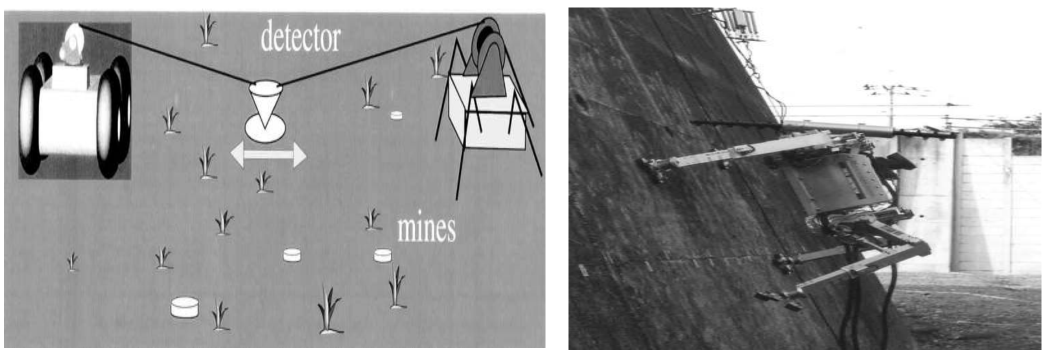


Fig. 2.1 Mine detection & removal (left) and Walking robot for slopes (right) [Perrin]

Figure 2.1 shows tethered applications for safety and rescue robotics. With the application of the “hyper-tether” concept to search-and-rescue mobile robots, further development can be expected [Hirose, 2000]. Hyper-tether research proposes the use of high-strength tether with built-in electrical conductors, which can be reeled-in and out by a winch or reel. It is important to note, that the winch/reel is carried on-board by the mobile robot itself. In this scheme, the tether can be reeled-in or out in synchronization with the robot movement, and the friction between the tether and the surrounding environment is kept to a minimum. The followings advantages of tethered based rescue robots are also relevant:

- The on-board battery can be of small capacity because it will be continuously charged through the tethers. This will lead to decrease in the total weight of the system.
- Highly reliable cable communication link can be established at no extra cost. Communication architecture based on wireless

communication technology might cause the robots to interfere each other and might also pollute the wireless communication spectrum.

- The tether can be used to drag the robot out from the debris in case of malfunction.

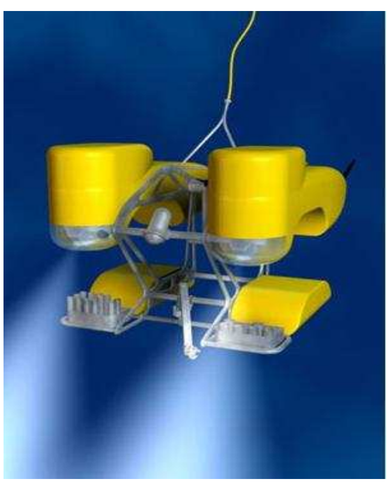
It is advantageous to deploy as many robots as possible to a disaster scene, so that they can work independently and in parallel to finish the rescue operation in minimum time [Shigeo, 2002]. However, some tasks such as removing heavy objects or overcoming high obstacles are difficult, if not impossible, to be performed by a single robot alone. In such cases, the cooperation among the robots can be an effective solution.

2.2 Underwater robotics

The vast majority of submersibles are operated in the tethered as opposed to autonomous free swimming mode. This is likely to remain the case as long as there is a need for prolonged periods of powered remote operation and real time data transfer [Abel, 1994]. Unmanned submersible applications and basic asset management principles should be more advantageous than using autonomous vehicles. If tether management is done proficiently, the operational capability of submersible is increased significantly. Tethered underwater water robotics can be used in: [Bowen, 2004]

- Detection of underwater mines.
- Surveillance and location identification of planes and ships wreckage or other debris at the deepest ocean depths quickly and efficiently.
- Investigation of volcanic and hydrothermal activities in the deepest portions of oceans.
- Investigation of ultra-slow spreading sea floor geology, biology and geochemistry (rock and fluids).
- Investigation of seismic, geo-hydrological and microbiological problems in the inward slopes of oceanic trenches in subduction zones.

Remotely Operated underwater Vehicles (ROVs) is the common accepted name for tethered underwater robots in the offshore industry. ROVs are unoccupied, highly maneuverable and operated by a person aboard a vessel. They are linked to the ship by a tether (sometimes referred to as an umbilical cable), a group of cables that carry electrical power, video and data signals back and forth between the operator and the vehicle. [Ocean explorer, 2007]. Submersible ROVs may be "free swimming" where they operate neutrally buoyant on a tether from the launch ship or platform or they may be "garaged" where they operate from a submersible "garage" on a tether attached to the heavy garage that is lowered from the ship or platform. Both techniques have their pros and cons. However very deep work is normally done with a garage. Bowen and others explained a preliminary design of a novel light-tethered Hybrid ROV (fig. 2.2) for exploring the deepest depths [Bowen, 2004]. It provides the US oceanographic community with the first capable and cost effective technology of regular and systematic access to world's oceans to 11,000 meters. The vehicle is capable of operating untethered as a fully Autonomous Underwater Vehicle (AUV) for benthic survey operations and also as a self-powered ROV for sampling operations. The ROV uses a very small diameter fibre optic tether. The function of the fiber optic tether is to transmit high bandwidth data only and not power. Lower density floatation has the significant benefit if systems have lighter weights and smaller sizes. For example, an AUV that is smaller and lighter can travel further underwater. The fiber optic tether for the system must be able to be precisely wound into deployment boxes in long lengths (20 km) in a manner that is light in weight and is pressure tolerant with respect to optical attenuation of the optical fibre.



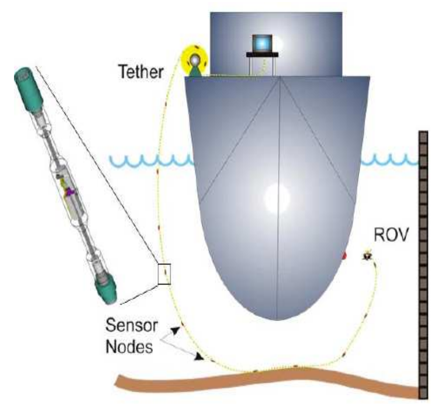


Fig. 2.2 HROV [Woods] (left) and Underwater tethered system [Frank] (right)

In a typical underwater tethered system, a surface buoy connects to a tether that isolates a subsurface float from surface buoy motions. The surface buoy provides power via a cable to a seafloor junction box, which accommodates a variety of sensors. Data from the sensors travel up the cable to the surface buoy for transmission via satellite to shore. Components of a typical underwater tethered system for underwater mines detection is shown in the following figure 2.2 (right).

2.3 Space robotics

In some degrees, satellites can be considered as robots because robot can be defined as “A machine used to perform jobs automatically, which is controlled by a computer” [Cambridge Online Dictionary]. Secondly, satellite qualifies most of requirements of robot like:

- Is not 'natural' / has been artificially created.
- Can sense its environment.
- Has some degree of intelligence or ability to make choices based on the environment or automatic control / preprogrammed sequence.
- Is programmable.
- Can move with one or more axes of rotation or translation.

A space tether is a long cable used to couple spacecrafts to each other or to other masses, such as a spent booster rocket, space station, or an asteroid [TUI, 2007]. Space tethers are usually made of thin strands of high-strength fibers or conducting wires. The tether can provide a mechanical connection between two space objects that enables the transfer of energy and momentum from one object to the other, and as a result they can be used to provide space propulsion without consuming propellant. Space tethers can provide capabilities for a number of applications including:

- Formation Flying Tethers
- Momentum Exchange Tethers
- Electrodynamic Tethers
- Electrostatic Tethers
- Tethered Rovers

A planetary exploration system traditionally consists of a lander and a rover. In a typical lander-rover system, the rover carries the Drilling & Sampling Subsystem (DSS) which is able to penetrate and sample the ground. Lander camera is used for navigation of rover. The rover is connected with the lander by a tether for power and communication purposes. During operation, the rover ejects from lander, goes to a point as guided by the lander camera, drills and collects planetary soil samples and finally returns back to the lander. Operational scenario of rover is shown in the fig 2.3. The tether can also be seen in this figure.

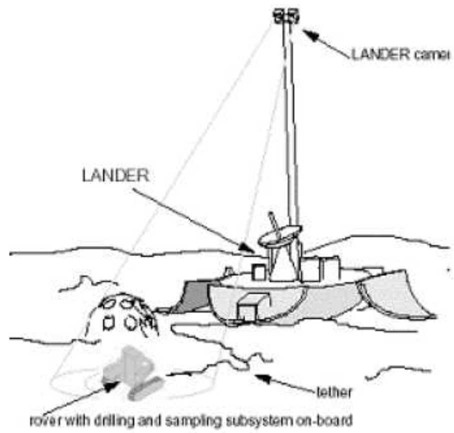


Fig. 2.3 Setup of a typical lander-rover system

Most famous planetary rovers using tethers are Nanokhod, MRoSA 2 and PROP-M planetary rovers, described in more detail below.

2.3.1 Nanokhod

The Nanokhod micro rover was embraced by ESA in the course of the "Micro-robots for Scientific Applications" activity as the most promising realization of an 'instrument deployment device'. The rover is designed so that the scientific sensor instruments can be accommodated in the central payload cab. The locomotion is performed by means of tracks. The locomotion system is able to position the payload cab with 2 Degrees of Freedom. The rover power and data connection to the lander is implemented through thin tether wires. The rover control and navigation is semi-autonomous: it exploits a 3D digital elevation model of the terrain, acquired by means of a panoramic camera on the lander. The thermal control is entirely passive while the electrical power peak consumption is 3 W. The total Payload mass is 1100 g. The rover mass without P/L is 1450 g. Figures 2.4 (left) shows the Nanokhod isometric view whereas Nanokhod in operation is depicted on right.

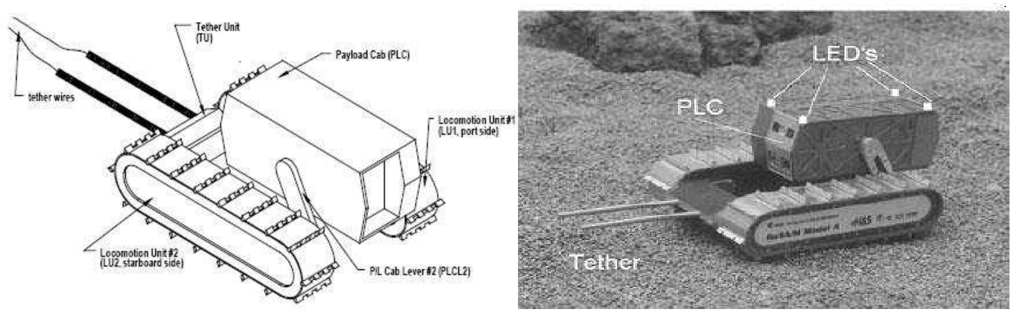


Fig. 2.4 Nanokhod isometric view (left) and Nanokhod rover (right) [ESA]

The actuators of the Nanokhod breadboard comprise: [Fontaine, 2000]

- The left track and right track locomotion motor, to allow the Nanokhod to move (track left, right, forward, backward, stop).
- The PayLoad Cab (PLC) articulation motor (PLC up-down-stop).
- The lever articulation motor (lever up-down-stop).
- 4 LEDs that can be individually activated, used for localization of the rover by the lander.

The sensors comprise:

- Odometers (as two magnetic encoders) to measure the rover motion.
- Angular encoders: one measuring PLC angle, other measuring the lever angle.
- Six contact switches at the front of the PLC.

2.3.2 MRoSA 2

In 1998, ESA initiated the Micro ROSA project. The overall objective of the project is to develop a Robotic Sampling System based on Nanokhod. This means to develop a drill capable of subsurface sampling (down to 2 meter depth) and modifying Nanokhod to be able to operate as a platform for this drill. The project was carried out in Finland by HUT, SSF and VTT. In 2002, the project got continuation in the form of MRoSA2 upgrade project. This also includes SW upgrades due to rover's tether reel repair to ensure smooth reeling [Anttila, 2004]. In MRoSA 2, the only improvement to the Nanokhod design from the requirements side was that the tether should be rewindable. [Suomela, 2002]. MRoSA 2 is depicted in fig. 2.5. The rover for this thesis (ROSA) has same structure as that of MRoSA but it does not currently have Drilling and Sampling Subsystem (DSS). Chapter 4 explains ROSA.

Fig. 2.5 MRoSA 2 rover in operation [ESA]

2.3.3 PROP-M

The Russian Mars landers carried a small, walking robot, “PROP-M” [Vniitransmash, 2002]. Because it did not have its own power source, it was tethered to the lander. The tether was 15 m of length and it also carried the communication line. The robot carried two instruments: a dynamic penetrometer and a radiation densitometer (called “GEOHI” RAS). The rover was onboard Mars-2 and 3, and later Mars-6 and 7 landers, which all unfortunately failed. The “ski-walking” rover is shown in figure 2.6. Mass of the rover was 4.5 kg whereas the dimensions were 215x160x60 mm. Travel speed was one metre per hour and the rover consumed 5 W of power. Russian Lavochkin Association produced the rover.

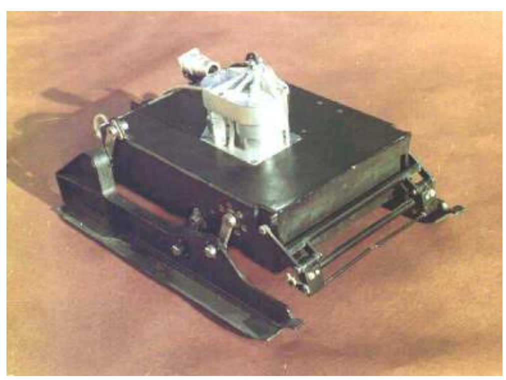


Fig. 2.6 The PROP-M ski-walking rover [RCL]

As shown in figure 2.6, the main frame of the PROP-M was a square box with a small protrusion at the center of the body. The rover had two wide flat skis, one extending down from each side elevating the frame slightly above the surface. Also seen in the picture are the obstacle detection bars in front of the rover. The rover was supposed to be lowered to the surface after landing by a manipulator arm and to move in the field of view of TV cameras. Then the rover was planned to stop every 1.5 meters to make measurements. The traces of movement in the Martian soil would also be recorded to determine material properties.

2.4 Other terrestrial tethered robots

Tether also finds its applications in hyper-tethered robots, petroleum tank inspection robots, volcanic exploration robots and a number of other terrestrial robots

2.4.1 Hyper-tether applications

The Hyper-tether concept has emerged as a result of recent research on tethered connections to provide tethering among different mobile robot types, such as a robot with the environment and a robot with humans and animals [Edwardo, 2001]. Hyper-tether's basic function is to actively control the tether's tension and/or length, but it also considers tether launching, anchoring, power delivery, data communication cabling and built-in trajectory command generation capabilities.

Walking machines have an intrinsic ability to move over rough terrain but their payload capability is rather limited. In contrast, crawler or wheeled robots offer great payload but they do not perform well on uneven terrain and steep slopes. A system of load transportation is shown in figure 2.7 (left), which combines both mobile robot types advantages. In this scheme, the walking machine stands on the top part of the hill, and after fixing firmly to the ground pulls the crawler upward. The downward motion can also be accomplished in the same way.

In the same way that rope has been a fundamental tool for mountain-climbing, hyper-tether hardware can become useful for assisting robots or humans moving on steep slopes, as shown in figure 2.7 (right). It is important tat the base interface be mounted on the mobile platform instead of fixing it on the ground. In this configuration, the tether is reeled in or out from the winch as the mobile platform moves and friction between the tether and the environment is avoided.

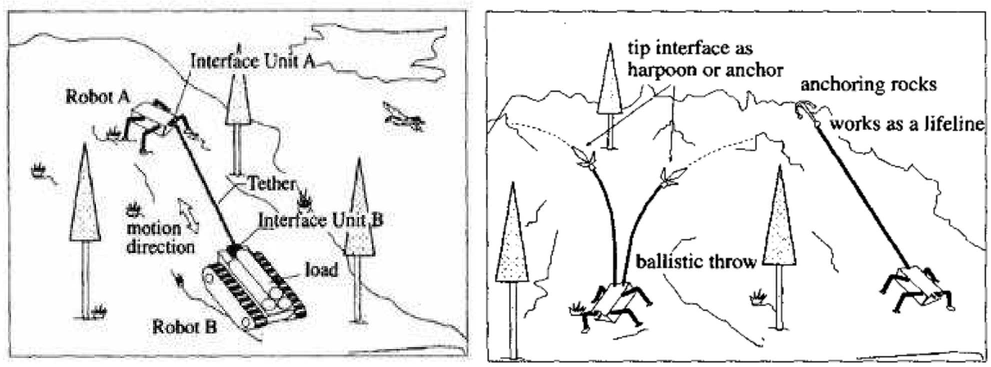


Fig. 2.7 Hyper-tether for motion (left) and anchoring rocks (right) [Edwardo]

Other potential applications for the hyper-tether include: (fig. 2.8)

- Cooperative material transportation
- Stable locomotion on steep slopes
- Locomotion of micro-rovers in micro-gravity environment
- Far-reach tethered working tool
    - Mine detection and removal
    - Weed removal
    - Conveyance of goods in mountainous areas
    - Trimming of gardens and grass cutting of wide areas, such as golf courses and soccer and baseball fields
    - Spraying of agricultural chemicals
    - Forestry and construction works

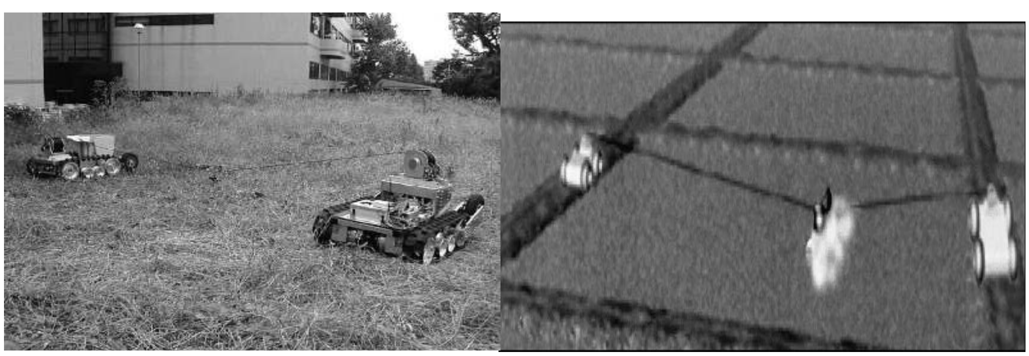


Fig. 2.8 Field scanning of hyper tether system (left) and Spraying (right) [Edwardo]

2.4.2 Petroleum tank inspection robot

For robots working in enclosed spaces e.g. pipes and tanks, hard-wired communication lines are the only means of guaranteed communication with the robot [Krishna, 1997]. The tether may also serve as a means of robot deployment (e.g. a robot lowered through an opening at the top of an oil storage tank) and could be used for robot retrieval in case of failure.

Example of tethered robots for tank inspection system includes Neptune system [Schempf, 1994]. It is a mobile robot system used to remotely inspect Above-ground Storage Tanks (ASTs) containing petroleum products. The robot system allows unmanned entry and sensor data collection in ASTs without the need to empty or clean the tanks nor the required human walkthrough inspection. The complete system is comprised of:

- A robot crawler vehicle (fig. 2.9) suitable for classified locations which carries visual and ultrasonic sensors. It is difficult or sometimes impossible for human to enter these locations.
- A deployment pod atop the tank which lowers and retrieves the crawler.
- An in-tank acoustic positioning system to chart and control the location of the robot.
- An external remote control console utilizing commercial and custom software for display, planning, and control tasks.

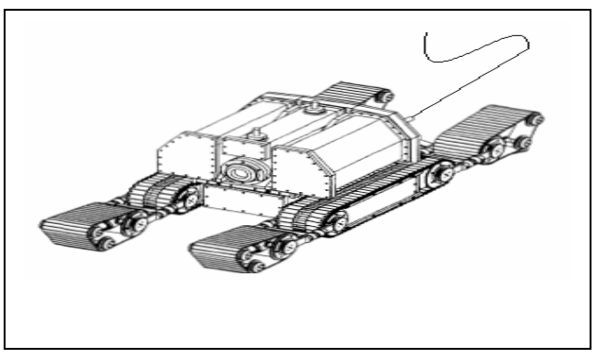


Fig. 2.9 Neptune: Tethered crawler [Schempf]

The sensors used on the crawler consists in part of a miniature color CCD camera aided by a low-temperature set of tuned halogen or LED lights to illuminate the path in front of the vehicle to allow the teleoperated tracking of weld seams. The ultrasonic measurement probe is attached to the rear of the vehicle and consists of a set of 8 in-line transducers mounted on a magnetic-wheel self leveling trolley. The Neptune system provides a visual record of each weld seam in the tank using an on-board color camera, as well as a thickness-contour map of the tank bottom plates using an ultrasonic steel-plate thickness measurement sensor array. The entire crawler runs on a 48 VDC power bus generated from 300VDC supplied through the tether. Other required voltages are generated internally using DC to DC converters.

2.4.3 Volcanic exploration robot

Volcano exploration using robotics is a very challenging case-study for tethering system design. Dante II is a tethered mobile robot designed for volcano exploration [Krishna, 1997]. It is an eight-legged rappelling robot that uses a tether to support itself on steep terrain, just as a mountaineer uses a climbing rope. The tether is connected to a generator and satellite communication station located at the volcano's rim. The satellite station relays data to and from remotely located operators.

Dante II is an example of volcanic exploration robot. An onboard tethering system manages the 300m of tether wrapped on a winch drum (fig. 2.10). The robot coordinates tether payout with leg motion to maintain an appropriate tether tension during the entire walking cycle. This is especially important while negotiating transitions in the terrain slope. The tether tension stabilizes the robot on steep slopes by counter-acting the moment that causes the robot to tip down the slope. The tether tension force also helps to increase the load on the uphill legs and thus equalize the loads on all the legs.

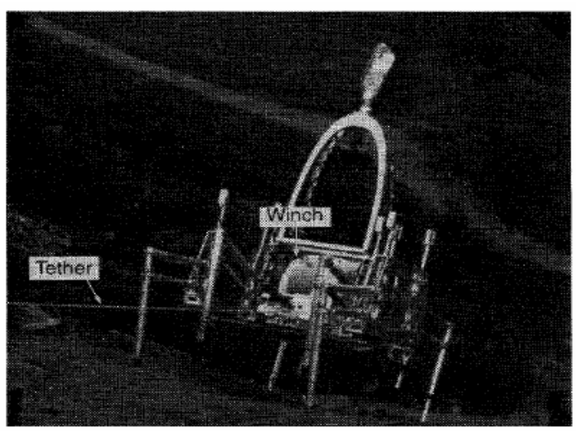


Fig. 2.10 Dante II at a field test [Krishna]

2.4.4 Non-robotic tethered applications

Non-robotic tethered systems include manually operated logging machines on steep slopes with a steel tether for support, high-altitude weather monitoring systems with a tether to anchor the weather balloon and provide power and communication to the balloon, and underwater exploration [Krishna, 1997]. Tethered meteorological kites have been also used for number of reasons including:

- They're cheap.
- They provide a stable platform.
- They can provide a continuous read of a cross section of the atmosphere since kites can sometimes be kept aloft for days at a time.
- They can be used over land, water or ice.
- Modern kites can reach dizzying heights, hoisting scientific payloads as high as several kilometers.
- They're low-tech, perfect for work in remote regions.

Beyond gathering weather data, some scientists are using kites to uplift insect traps high into the atmosphere to study insect migration. For flying in a temperate climate, a car winch is employed [Devitt, 2000]. The winch uses a capstan attached to the raised drive wheel of the vehicle to control the kite tether and to let out and pull in the kite under high tensions (fig. 2.11). If the car is reversed, the line reels out. If the car is parked, the line stays still whereas putting the car in forward lets line reel in. In a frigid climate, an electric winch powered by a small gasoline generator can be used. By adjusting the angle of its wings, under automatic control, a WindTRAM (Tether Rover for Atmospheric Measurements) invented by Mike Jensen scurries up and down the kite line, carrying the scientific payload. For recording altitude, a pressure altimeter can be used. If differential GPS receivers were placed on both the kite and on the ground, it would be possible to measure altitude within inches.

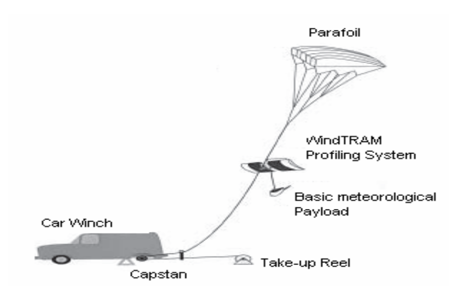


Fig. 2.11 Tethered meteorological kite [Devitt]

Chapter 3

Tether tracking systems

A tether can be tracked by systems based on proximity sensors or tactile sensors. Moreover vision based imaging system based on a camera can also be used by a robot to follow the tether. The first section presents proximity sensor based systems. Two main sensors ultrasonic and IR have been discussed. The next section discusses tactile based sensory system. Finally vision based tether tracking system has been briefly explained. These methods along with their advantages and disadvantages have also been discussed in this chapter.

3.1 Proximity sensor based systems

Proximity sensors detect the presence of nearby targets without requiring any contact or wiring to the target or any particular target material properties. These sensors are used for many industrial applications and they are available with a variety of analog and digital outputs. Various sensors are available for proximity detection and measurement, including capacitive, inductive, optical, ultrasonic and magnetic sensors.

3.1.1 Ultrasonic

Ultrasonic sensors radiate a short ultrasonic pulse in 20 KHz – 500 KHz range, above the normal limits of human hearing. The pulse bounces off a local object and the echo is observed (fig. 3.1). Echo intensity depends on the transmission of air and the sonic reflectivity of the target, which is a function of the orientation and material of its surface. Large sized objects with hard surfaces return the best readings. Objects made of soft fabric or those which are curved (like a ball) or are very thin or small can be difficult for the sensor to detect. The speed of ultrasonic waves is 340 m/sec. Ultrasonic waves can be used to measure distances from 1m to approximately 50m. Table 3.1 summarizes applications of ultrasonic sensor in robotics.

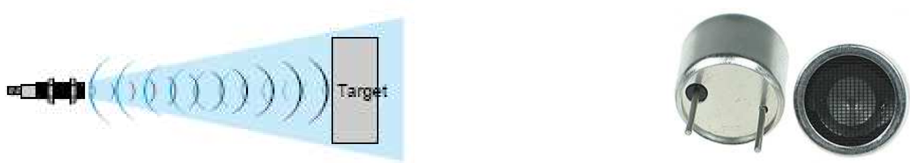
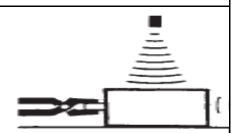
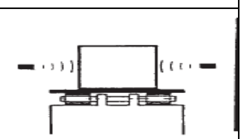


Fig. 3.1 Ultrasonic sensors: Working principle (left) and Typical sensor (right)

Table 3.1 Ultrasonic sensor robotic applications

Description	Application	Scenario
- Wind and unwind control - Roll diameter measurement	- Robotics - Paper processing	
- Distance measurement - Work piece positioning for robotics - Height measurement	- Robotics - Automotive	
- Part presence/absence sensing	- Robotics - Assembly equipment - Material handling	

The Ultrasonic Sensor is one of the two sensors that give the robot vision. (Light sensor is the other). The Ultrasonic Sensor enables the robot to see and detect objects. It can also be used by the robot to avoid obstacles, sense and measure distance, and detect movement. For terrestrial robotics applications employing tether, ultrasound sensor can be one of choice but it is not recommended for environments like that on Mars because of the extremely low pressure. The pressure of Mars's atmosphere varies with the season, ranging from 6 to 10 millibars (1 millibar is approximately one-thousandth of the air pressure at the surface of Earth). Hence an ultrasonic sensor has not been selected for tether tracking of ROSA.

3.1.2 IR

Infrared (IR) radiation is electromagnetic radiation of a wavelength longer than that of visible light, but shorter than that of radio waves. IR radiation has wavelengths between approximately 750 nm and 1 mm. The infrared portion of the spectrum has a number of technological uses, including target acquisition and tracking by the military, remote temperature sensing, short-ranged wireless communication, spectroscopy and weather forecasting. Fig. 3.2 shows IR reflective mechanism.

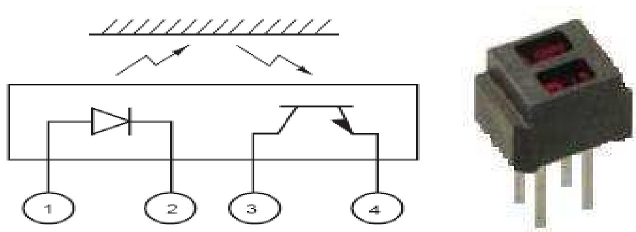


Fig. 3.2 IR sensors: Working principle (left) and Typical sensor (right)

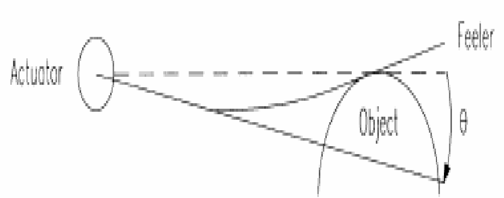
IR sensors are quite cheap, simple and robust but they suffer with the interference from ambient light. This is the key issue in IR sensor operation. Secondly, IR sensor work perfectly and give best results if the reflected surface is either black (perfect absorber) or white (perfect reflector). This challenge also needs to be addressed while developing a system based on these sensors. Though challenging but IR sensor has been considered as suitable option for tether tracking in ROSA because of its inherent advantages.

3.2 Tactile sensor based systems

Tactile sensors are based on direct mechanical contact between the sensor and the object of interest. These are typically employed on automated guided vehicles and mobile robots to provide indication of collisions with surrounding obstructions. Tactile sensors are extremely reliable and are used in mobile robots as “last limit”.

3.2.1 Active curb feeler (Whisker)

Many species of animals and even some plants use whiskers as a sensory structure. Passive feelers rely on the relative motion between the robotic platform and the sensed object. Active feelers are independently swept through a range of motion by their own dedicated actuation schemes. Kaneko [Kaneko, 1994] described a system that uses a small rotary actuator to manipulate a flexible feeler in the horizontal plane. This configuration consists of an insensitive flexible straight beam, together with a motor, torque sensor and rotation encoder at the whisker root. This sensor used an active motion to detect the contact point between the sensor and an object. Initially the whisker was moved into contact with an external object. An additional angular displacement was then applied at the root of the whisker, causing it to bend (fig. 3.3). The point of actual contact along the flexible feeler can be determined by measuring the amount of rotation after initial contact and the corresponding induced torque. By duplicating the sensors and actuators this active antenna sensor can scan in two orthogonal directions. A typical whisker sensor kit is also shown in figure 3.3.



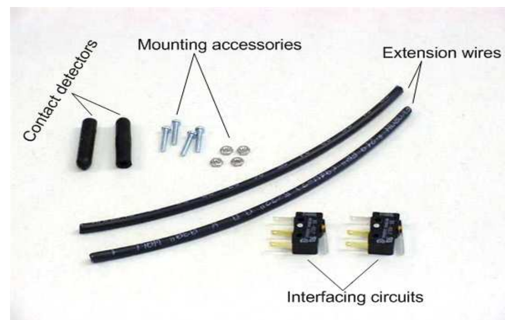


Fig. 3.3 Active feeler configuration (left) and Typical whisker sensor kit (right)

Operation and performance of a whisker is highly dependent on mounting of the sensor relative to object under detection. In ROSA, the object under detection (tether) is highly flexible. It can bend at any angle from any position in front of rover. Secondly, the width and thickness of tether is significantly small, so it made tether tracking cumbersome by direct mechanical contact. Because of these factors and geometrical dimensional considerations, the idea of using whisker sensors for tracking ROSA tether was no more considered.

3.3 Vision based systems

The tether control system based on vision-based sensors (camera) employs image processing and filtering techniques. Image from the camera may be first filtered and then the position of target-path (tether) in the image is evaluated using best possible match (correlation function). This can be scaled and translated into track motor commands to move certain degrees in a specific direction.

Vision based systems are most accurate but their implementation is quite intensive. In case of ROSA, there is not tough requirement of accuracy. Because the rover has to finally reach the lander after collection of samples, so there is no problem if the rover has a little drift around the flexible tether. Secondly, vision based systems are far much expensive as compared with the methods based on tactile or proximity sensors. Hence, these are not considered incase of ROSA.

Chapter 4

ROSA

This chapter gives an overview of ROSA. First part of this chapter describes the ROSA platform. Different subsystems (SS) of ROSA are then listed. Because of relevance with the thesis topic, tether, locomotion, control and power subsystems are explained in detail. Higher level architectural block diagrams are used to describe these SS. Electrical as well as mechanical aspects are presented.

4.1 Platform

After Viking and Pathfinder missions it has been noticed that sampling surface material gain little scientific information. In the view of the results of these missions, and of the ESA Exobiology Science Team Studies, the scientific investigators now require subsurface sampling [ESA 1998].

If used for exploration, the ROSA rover moves in a certain range around a lander and have a task to perform analysis, to sample surface material and to feed analysis instruments for investigations. ROSA is designed with the emphasis on the optimal integration of its payload. The core of the vehicle is the central payload cab, suspended in the center rotation axis by two levers. The payload cab can accommodate the Drilling and Sampling Subsystem (DSS) and control electronics. It is articulated in two dimensions. In the middle of the payload cab there is a joint that allows pitching of the payload cab. This allows sampling at angles ranging from vertical to horizontal. The payload cab can be rotated ±180° around its axis, in order to place both ends of the box in front of the chosen location without moving the rover.

The levers provide two DoF to position the payload cab. These levers also connect the payload cab to two side bodies that contain sealed tracks. The payload cab can also be lifted, which allows adjusting the ground clearance of the payload cab. Payload cab serves as a platform for DSS. Its function is to enable the DSS to sample in desired locations and to deliver these samples back to the lander. ROSA has two tracks, which make it capable of operating in difficult terrain. The tracks are actuated with independently controlled DC-motors. The actuators with corresponding equipment are located inside the tracks. Figure 4.1 shows overview of these details.

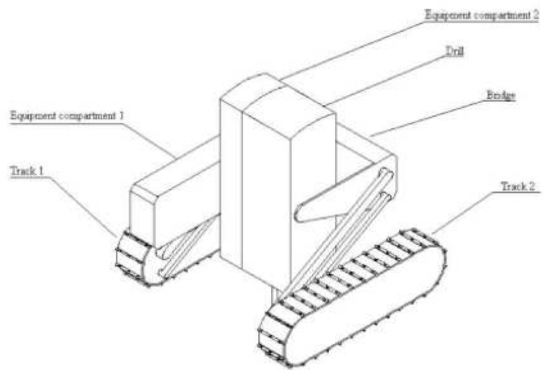


Fig. 4.1 ROSA overview

The lander-based camera can be used, in combination with a laser pointer, for navigation. The path planning can be based on waypoint that operator selects. Thus, the target and the roving path can be selected by the operator with the aid of the image from the lander-based camera.

For proper thermal control, ROSA can be equipped with any active thermal control. Secondly, all the components are required to withstand temperature conditions from -140°C to +70°C.

4.2 Subsystems (SS)

The whole system has been divided into several subsystems. Main subsystems include locomotion SS, tether SS, control SS, power SS, auxiliary SS and processor unit. The version of ROSA used for this thesis does not have the drilling and sampling SS (DSS). Figure 4.2 shows these subsystems. The control subsystem does all the computing and the communication. It also contains all the needed controllers. The

Power subsystem provides energy for the other subsystems. The rest of the subsystems include actuators that are controlled and sensors that give feedback about the current state of the system. The lander is also shown in the figure. This is due to its crucial role in the ROSA operation. The lander is needed for the power supply and for the communication. Moreover, the navigation of the ROSA is also dependent on the lander-based camera. DSS is also shown in the system to make ROSA system meaningful.

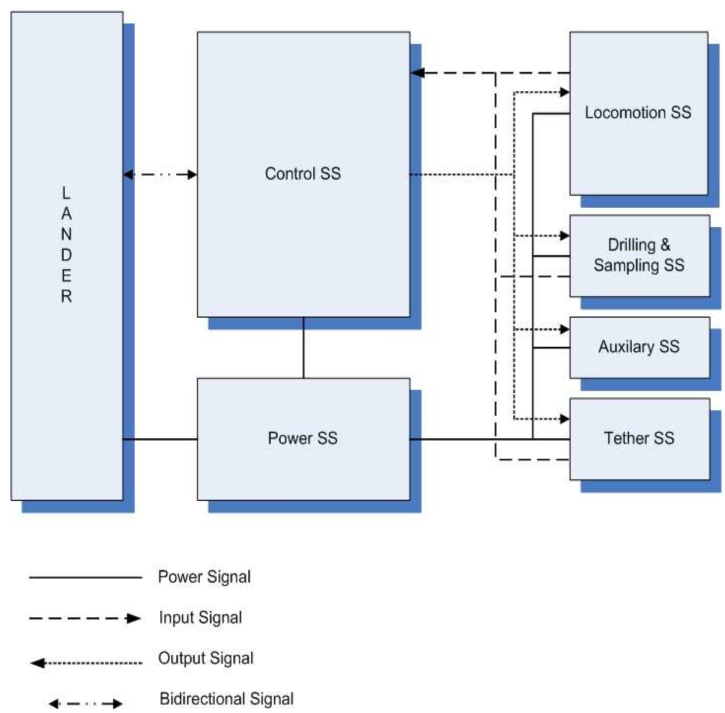


Fig. 4.2 ROSA system with lander

4.2.1 Tether SS

Because of very strict mass and volume constraints, neither batteries (requiring thermal control) nor solar panel can be accommodated on the rover. Thus, one alternative is to transfer the energy from the lander to the rover through the tether. The tether can also be used for telecommunication. The tether, however adds some operational requirements to rover path planning. First, driving over the unrolled tether should be avoided. Secondly, the length of the tether limits the total accumulated travel distance. Making the tether longer would increase the mobility, but would also increase the power consumption and require more volume in the tether bridge. A self-deployment of the tether is required i.e. the tether is pulled out as the rover moves forward. Table 4.1 shows the typical details of tether in ROSA. The length of the tether cables is sufficient to cover the minimum total accumulated travel distance.

Table 4.1 Tether characteristics

Feature	Description
Length	40 m
Width	1.5 cm
Material	Kapton
Color	Yellowish Orange
Composition	5 sub wires

The selection of the cable was made according to the wide operating temperature range (from -73°C to 260°C) of the Kapton. Also the very thin structure was considered as an advantage when making the selection. Especially when rewinding the tether, flat structure of the Kapton is very practical. The tether has five circuits in it: two for the power supply and three for the serial link. A slip ring is used as a rotating joint between the reel and the body of the payload cab.

The main computer is controlling the tether reel with two small motors. First is reel motor and the second one is feed motor. Both of the motors are 1.2-W DC-motors with precious metal brushes. The motors are gear motors, which mean that they have an internal gear. Table 4.2 shows details of these motors. Figure 4.3 shows tether Data and Control Handling Hardware (DCHH) block, which is presented in chapter 5.

Table 4.2 Tether motors characteristics

Characteristics	Tether Motors
Motor type	Maxon 167170
Motor diameter	20mm
Brush type	Precious metal
Supply voltage	12VDC
Assigned power rating	1.2W
No load speed	12800

Stall Torque	72.7mNm
No load current	15.97mA
Starting current	153mA
Max.-continuous current	108mA
Attached encoder	Digital magnetic 16cpt
Internal gear	55.1:1
Motor control	Variable speed

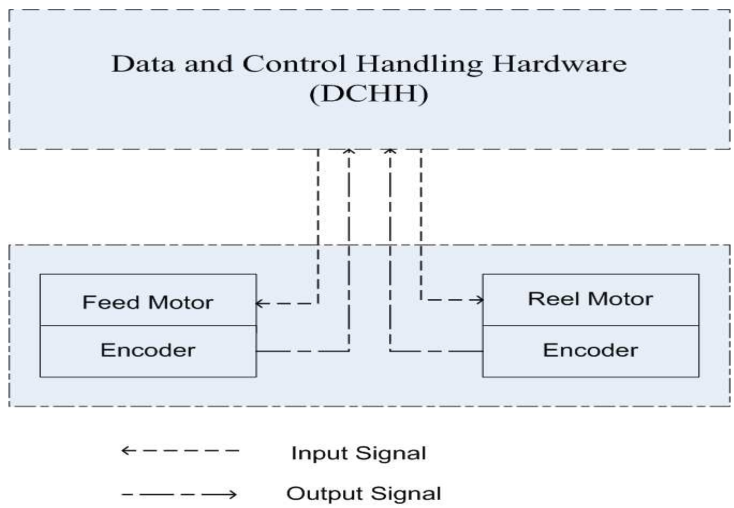


Fig. 4.3 Tether SS

The feed motor is used to control the rewinding and unwinding speed of the tether. The control loop compares pulse chains from the encoder of the feed motor and encoders of the traction motors. According to this ratio the PWM output for the feed motor controller is adjusted.

The reel motor has two operational modes. When unwinding the tether, the reel motor operates as an electrical spring and provides a constant resistance to keep the tether tensioned. When rewinding the reel motor operates with full power to rewind the tether as tight as possible.

The amount of the cable on the reel can be determined by comparing the pulse chains from the encoders. Control of motors is presented in the next chapter. Figure 4.4 shows mechanics and a snapshot of the ROSA tether.

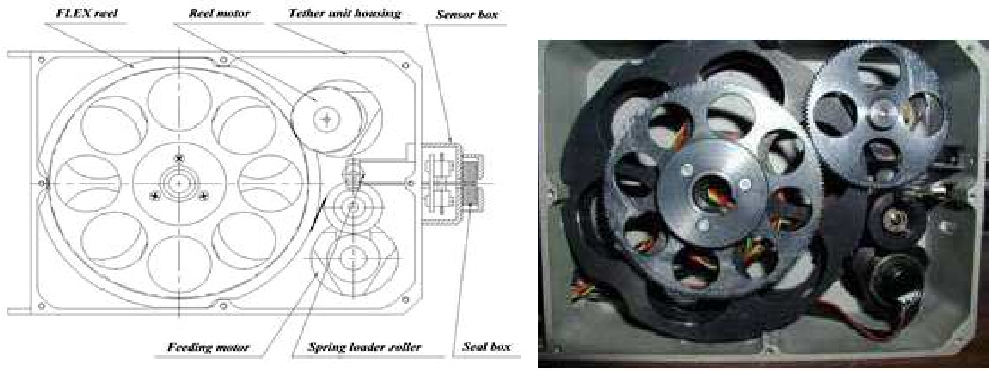


Fig. 4.4 ROSA tether: Mechanics (left) and Snapshot (right)

4.2.2 Locomotion SS

The locomotion subsystem is responsible of the movements of ROSA. These movements include the actual roving and the articulation of the payload cab. This section discusses the electrical and mechanical aspects of the locomotion subsystem. Locomotion subsystem consists of two units:

- Locomotion unit
- Articulation unit

The locomotion unit contains two motors and two encoders. The encoders attached to the traction motors are the only electronics in the locomotion unit. These encoders are connected directly to the counter inputs on the PWM board. The counters produce 16 pulses per revolution. Thus

Maximum pulse frequency = 16 *10500rpm / 60s/min

= 2800 Hz

The articulation unit also contains two motors and two encoders. However, these encoders are not connected to any input. They do not provide any information, but were attached for possible future purposes. It was easier to assemble them together with motors than to add them later on. The motors of articulation unit have been tested by giving direct voltage input. They can be connected to motor controller unit as shown in figure 4.5. Table 4.3 shows description of motors in locomotion SS.

Table 4.3 Locomotion motors specifications

Characteristics	Traction Motor	Payload cab lifting motor	Payload cab Pitching motor
Motor type	Maxon 110164	Maxon 110164	Maxon 110140
Motor diameter	22mm	22mm	22mm
Brush type	Graphite	Graphite	Precious metal
Supply voltage	24VDC	24VDC	24VDC
Assigned power rating	6W	6W	3.5W
No load speed	10500	10500	6520
No load current	23.7mA	23.7mA	4.33mA
Starting current	1100mA	1100mA	411mA
Attached encoder	Digital magnetic 16cpt	Digital magnetic 16cpt	Digital 100cpt
Attached planetary gearhead	84:1	231:1	53:1
Motor control	Fixed speed	Fixed speed	Fixed speed

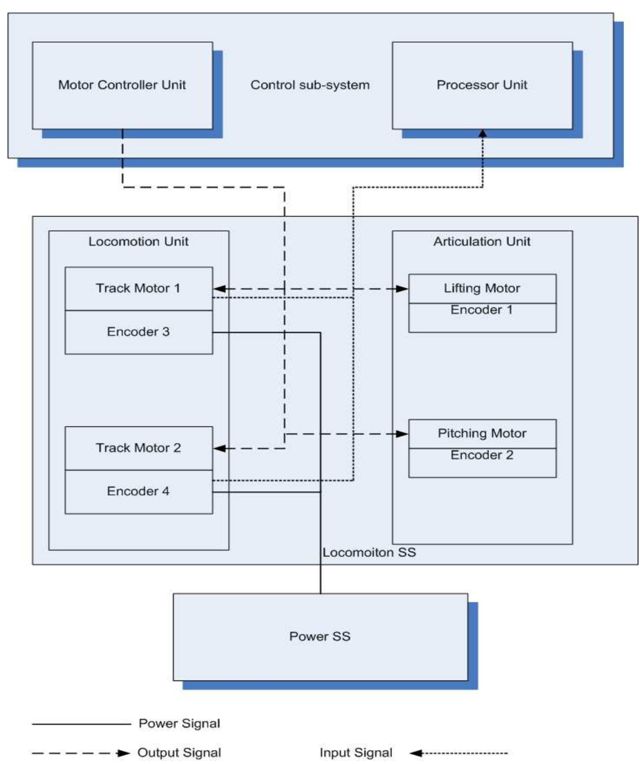


Fig. 4.5 Locomotion SS

The mechanics of ROSA has been designed keeping in view structural stability issues and additional constraints imposed by Mars environment. The tracks in ROSA look more or less like tracks in military tanks, but there is also the side covers to protect the motion motors and batteries from the Mars dust. The tracks have been designed and fabricated to move as easy as possible with the bearings, which are located between the track and body. Track bodies have been made from steel and Aluminum. The tracks can be moved in different directions and this causes the turn of the whole body. Movement distance, speed and directions of the each track have been accomplished with the encoders, which are located in the back part of each motor. The computer and the drill are located at the top part of the base. Top part is connected to the tracks with the Aluminum levers. These levers also include the flat cables, which contains wires from the motors, encoders and batteries. Figure 4.6 shows mechanics and track snapshot of ROSA tracks.

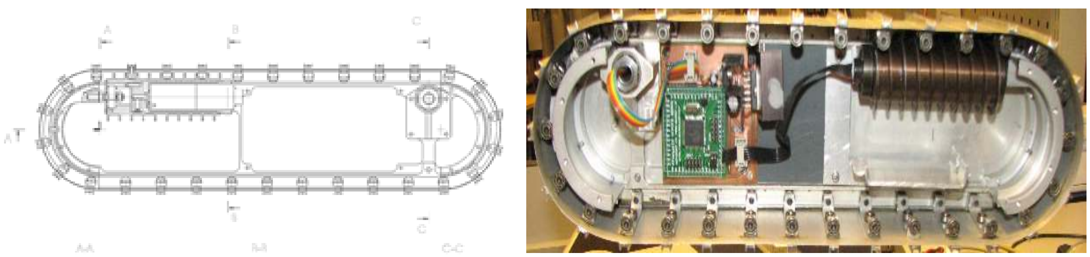


Fig. 4.6 ROSA track: Mechanics (left) and Snapshot (right)

4.2.3 Control SS

The control subsystem can be considered as the brain or central control unit of ROSA because it controls all the actions and processes all the input signals. The control subsystem acts as an interface between the software and the actuators and sensors. According to these signals it produces the required low-level functions. The control subsystem is also combination of Commercial Off The Shelf (COTS).

The control subsystem is further divided into four separate units, processor unit, motor controller unit, optional encoder signal converting unit, and output controller unit. These units are shown in the figure 4.7.

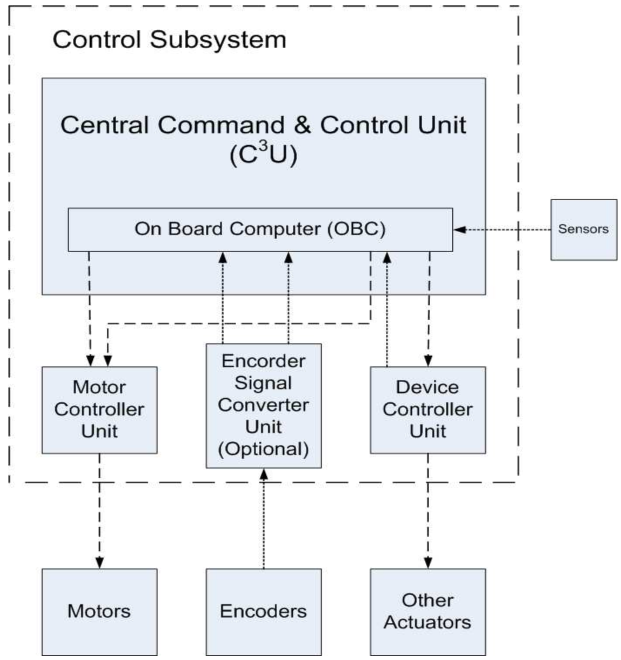


Fig. 4.7 Control SS

C^3U consists of On-Board Computer (OBC), DC-DC converter, PC104 CAN interface card and Distributor circuit. Block diagram of C^3U interfaced with right mobility system is shown in figure 4.8.

A Pentium III equivalent single board system (Ampro ReadyBoard 710) has been selected as an OBC. It is low cost, high performance and easy to interface system. It is used for high volume, compact embedded applications that need high performance, high-speed I/O and low power applications. Reason for its selection can be evident from its features. (Table 4.4)

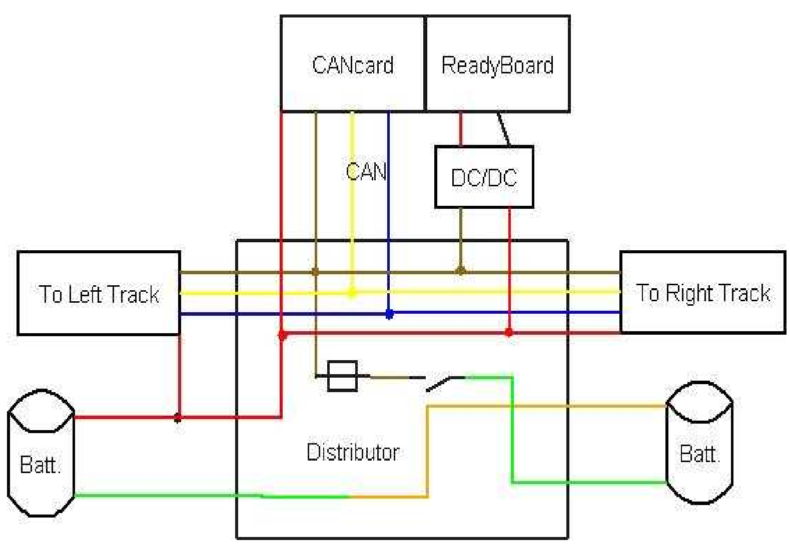


Fig. 4.8 C^{3}U block diagram

Table 4.4 OBC features

Feature	Description
Processor	650 MHz Ultra low voltage Celeron
I/O	-4 Serial -4 USB 2.0 -1 Parallel – EPP/ECP bidirectional port -PS/2 interface -GPIO – Eight digital I/O pins -Audio – AC97 speaker, mic, headphone -AGP Video Interface
Network interface	Dual Ethernet – Gigabit and 10/100BaseT
Power req.	4.0A @5V
Dimensions	114.3 x 165.1mm

A DC-DC converter manufactured by Fabrimex (ECW 24-0525) has been used in C^{3}U to provide steady output voltage of +5V for the OBC and electronics of mobility system. Details of PC104 compatible CAN interface card are presented in communication architecture. The distributor board is just to distribute power to different sections. It consists of simple jumpers, switches, connectors and an opamp.

4.2.4 Power SS

ROSA is powered from the lander through the tether. There are two circuits reserved for power transmission in the tether. Thus, only one voltage level, namely 24 V, can be provided. Figure 4.9 shows the overview of the power subsystem.

Most of the motors operate on 24 volts. However tether motors were available only with 12 volts supply power. Motor drivers (H-Bridges) can be operated on 12V or 24 V. The computer and sensors require 5 volts supply power. Moreover the operational amplifiers, CAN Tx/Rx, controller and IR sensors on proposed hardware do require +5 V to operate. Thus, a DC/DC converter is needed in the power subsystem.

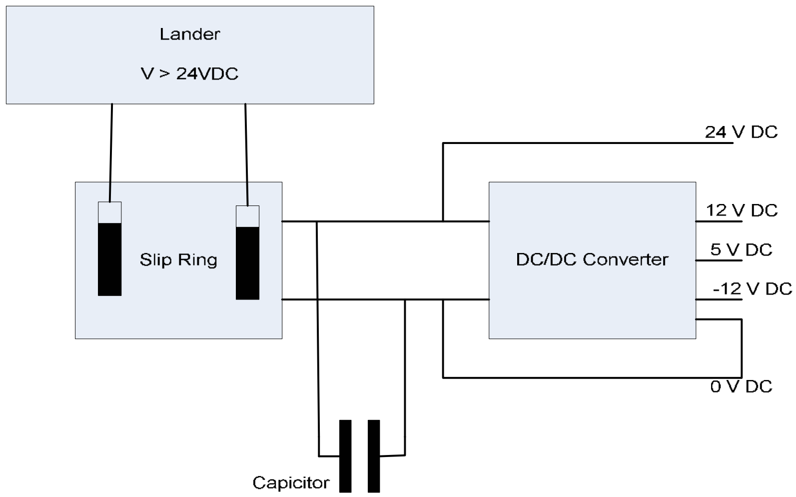


Fig. 4.9 Power SS

The capacitor (2200uF) is connected in parallel with the power supply is used to smooth short voltage drops and peaks. The slip ring is located inside the spool, which enables the connection between stationary rover body and rotating tether spool. Litton AC6023 slip ring has been used. Apart from power through tether, there is also possibility to accommodate batteries for backup inside ROSA.

Chapter 5

System implementation

This chapter discusses different aspects of the proposed system. Hardware, mechanics, software and algorithm implementation details are presented. Architectural block level design for each case has been explained followed by schematics/drawings or flow charts to reflect the step by step details of the development process.

5.1 Hardware architecture

The whole activities on the rover are being coordinated and controller by C^3U. A brief outline of C^3U has been discussed in chapter 4. This section explains design and implementation details of designed hardware. Tether tracking system can be grouped into two well-defined parts.

- Front-end sensing system
- Data and control handling hardware

5.1.1 Front-end sensing system

The sensor for the tether following robot needs to be able to distinguish between the black colour assembly and tether. One difference between black surfaces and tether is that black surfaces absorb all wavelengths of light while tether reflects some wavelengths of light. This property has been used to find the position of tether. IR sensors will be used instead of visible light sensors because visible light sensors are comparatively more easily interfered with by ambient light and shadow than IR. The longer wavelength of IR creates a stronger and more reliable signal while still being absorbed by the black colour.

Choice of proper IR sensor required some prototyping. Sensors which have been considered for selection are tabulated in table 5.1.

Table 5.1 IR sensor selection

IC	Manufacturer	Reflective Distances	P/Consumption
QRB1113 QRB1114	Fairchild Semiconductor	3.81 mm → 12.7 mm	100mW
OPB608 A,B & C	OPTEK Technology Inc.	1.27 mm→ 9.525 mm	100mW
OPB608V		1.27 mm→ 38.1 mm	
HOA2498	Honeywell	2.54mm→ 1.524cm	75mW

Initially OPB608V was selected but it was rejected on availability and economical grounds. Then OPB608A was ordered. It was expected to detect the tether the distance from distance of 1.27 mm (minimum) to 9.525 mm (maximum). After prototyping, it was found that the even using a white surface (pure reflective), the sensor can only detect the reflections up to maximum distance of 4 mm. Hence it was discarded. Finally, HOA2498 was selected and tested successfully. Its response (collector current vs distance to reflective surface) is shown in figure 5.1.

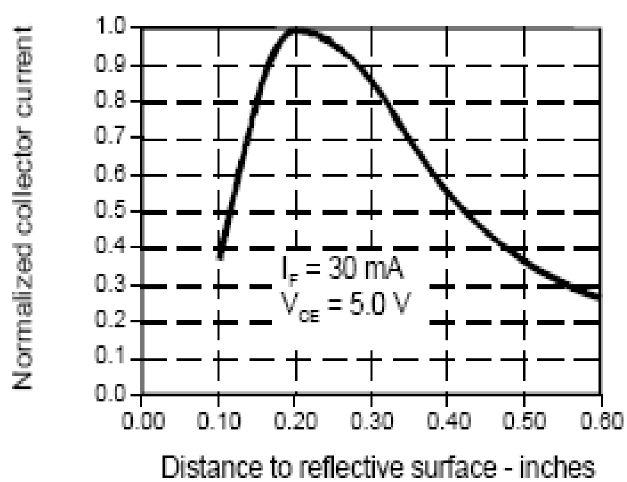


Fig. 5.1 IR sensor response

There will be five sensors used to keep the robot following the tether. Arrangement of these sensors was critical. Following possibilities have been evaluated.

i. V
ii. Inverted V
iii. Rectangular
iv. Semi circular
v. Zig Zag

For each case there can be different positions of sensors on the assembly. Factors which have been kept in mind for selection of array arrangement and sensor placement on assembly include:

- Sensors should be at suitable position to make tether detection system reliable.
- All of five sensors justify their presence on the array. So, there should not be any sensor which is not on at any time or which is off all the time during rover movement.
- Sensor should be close enough to have maximum possible combinations of "ON" sensors when the tether is under them.
- Sensor should not be too much close to start cross-talking.
- Practical soldering area consideration should also be kept in mind while finalizing sensor to sensor spacing.
- It is obvious that a pair of sensors would be tracking the tether on right, second pair on left whereas the fifth sensor monitors the tether presence in straight path.

These facts and experimentation with different sensor arrangements favoured to have zig- zag sensor arrangement. Figure 5.2 (left) shows the front end assembly drawing for this kind of arrangement. This figure is not per actual scale. Hence, corresponding dimensions are summarized in table 5.2. The assembly is two fold. The upper fold has five holes on it corresponding to five IR sensors. The lower fold is just a solid piece. The thickness of the sensor assembly is 2 mm. Tether is passed through this assembly. This allows freely winding and unwinding of tether. Figure 5.2 (right) illustrate this setup, in which the tether is passing through the centre of assembly. Hence, only the central sensor would be "on".

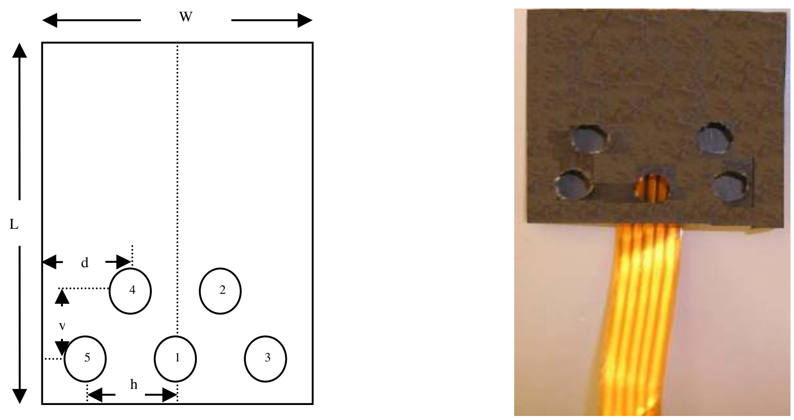


Fig. 5.2 Front end mechanics: Drawing (left) and Tether assembly (right)

Table 5.2 Front end assembly parameters

Symbol	Description (cm)
L	5.7
W	6.0
h	1.8
v	1.3
d	1.7
Hole Dia	0.8

Electronics of front end is straight forward. Schematic is shown in appendix A, whereas the snapshot of actual implementation is shown in fig. 5.3.

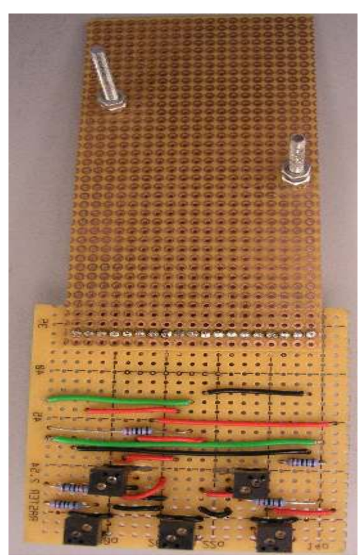


Fig. 5.3 Front end electronics

The assembly is mounted perpendicular to the point where tether comes out of the rover (tether-rover joint point). At this point, sensors in sensor assembly electronics are looking through the holes to see that which sensors detect tether presence beneath them. This sensors information is then given to the Data & Control Handling Hardware (DCHH), which is discussed in next section.

5.1.2 Data and control handling hardware

DCHH is the core hardware of tether tracking system. It provides real time control over tether motors and real time signal processing & analog to digital conversion of sensor data from front-end. DCHH hardware has following key features:

- CAN TX/RX interface
- Processing of sensor data
- Motor control for reel motor
- Motor control for feed motor

DCHH comprises of microcontroller, CAN transceiver, regulator, current filtering circuit and motor driver H-Bridge. Block diagram of designed hardware is shown in figure 5.4.

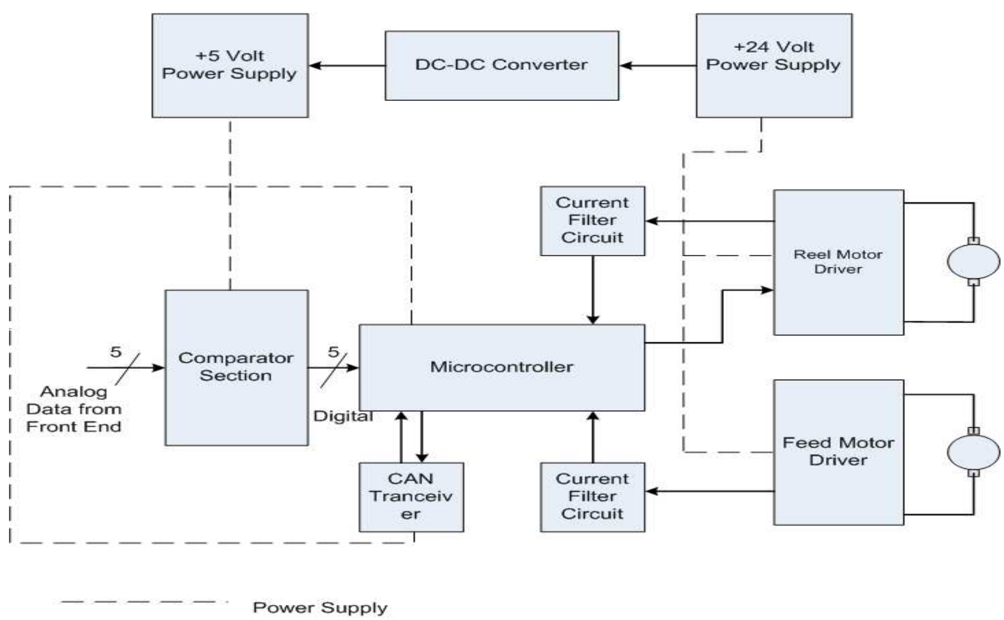


Fig. 5.4 Data & Control Handling Hardware

The motor controller is based on AVR-H128-CAN processor board. The processor board incorporates Atmel AT90CAN128 microcontroller. It is a low-power CMOS 8-

bit microcontroller based on the AVR enhanced RISC architecture. By executing powerful instructions in a single clock cycle, the AT90CAN128 achieves throughputs approaching 1 MIPS per MHz allowing the system designer to optimize power consumption versus processing speed. [AT90CAN128 Data Sheet]. Important features of processor board are listed in table 5.3.

Table 5.3 Microcontroller description

Feature	Description
Flash	128 KB
EEPROM	4 KB
RAM	4 KB
I/O Lines	53
Operating Voltage	5V
Clock Freq.	16 MHz
Operating Temp.	-40°C to +125°C

The microcontroller has on-chip 2.0A & 2.0B CAN controller having 1Mbits/s maximum transfer rate at 8 MHz. It has following operational mode: Transmit, Receive, Automatic reply and Frame buffer receive modes.

Texas Instruments SN65HVD230 has been selected as CAN transceiver because of its data rate support of 1Mbits/s, which makes it perfect to interface with the microcontroller CAN controller. It is specially designed for operation in especially-harsh environments; these devices feature cross-wire protection, loss-of-ground and over-voltage protection, over-temperature protection, as well as wide common-mode range. It incorporates features of thermal shutdown protection, open circuit fail-safe design and glitch free power-up and power-down protection. Logic diagram of SN65HVD230 is shown in figure 5.5.

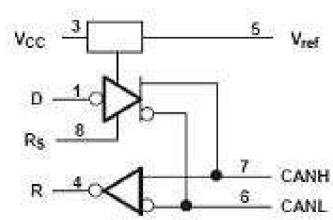


Fig. 5.5 CAN TX/RX logic diagram

CAN transceiver provides three different modes of operation, which can be selected by pin 8 (Rs). These include:

i. High speed
ii. Slope control
iii. Low-power modes.

To make sure that no frame is missed, we have used the CAN transceiver in high speed mode and thus pin 8 has been connected to GND, allowing the transmitter output transistors to switch on and off as fast as possible with no limitation on the rise and fall slopes. Hence the bus state is dominant as illustrated in function table (table 5.4) of driver, whereas function table of receiver is shown in table 5.5.

Table 5.4 Driver function table

Input D	Rs	Outputs		Bus State
		CANH	CANL	
L	$V_{(Rs)} < 1.2$ V	H	L	Dominant
H		Z	Z	Recessive
Open	X	Z	Z	Recessive
X	$V_{(Rs)} > 0.75$ Vcc	Z	Z	Recessive

The symbols key is

H = High Level
L = Low Level
X= Irrelevant
? = Indeterminate
Z = High Impedance

Table 5.5 Receiver function table

Differential Inputs	Rs	Output R
$V_{ID} \geq 0.9$ V	X	L
$0.5 < V_{ID} < 0.9$V	X	?
$V_{ID} \leq 0.5$ V	X	H
Open	X	H

The motor is driven by a LMD18200 H-bridge, capable of providing 3A continuous output. The motor speed and direction are controlled by separate signals. The H-bridge provides current sense output for motor current information and a thermal warning flag (at 145ºC). An H-bridge is built with four switches as shown in figure 5.6. These switches can be solid-state or mechanical. Table 5.6 summarizes two stages of H-bridge.

Table 5.6 H-Bridge stages

Operation	Direction	Figure
S1 & S4 = Closed S2&S3 = Open	Forward	5.7 (a)
S2 & S3 = Closed S1&S4 = Open	Reverse	5.7 (b)

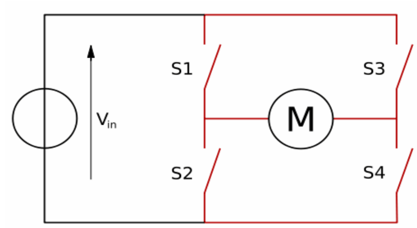
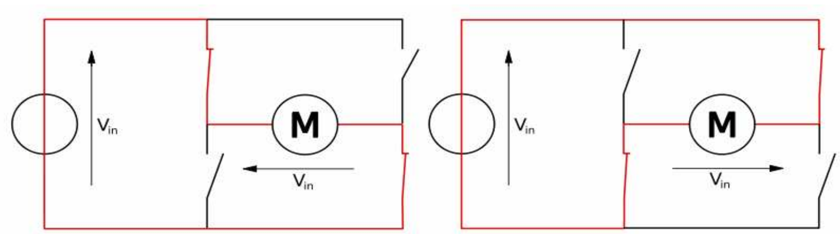


Fig. 5.6 H-Bridge operation



(a) (b)

Fig. 5.7 H-Bridge stages

LMD18200 H-bridge has been chosen on the basis of its quite enough current delivering capability. It accommodates peak output currents up to 6A and 3A continuous output current, which makes it ideal for driving DC and stepper motors. It provides a Brake input, which is used to brake a motor by effectively shorting its terminals. Figure 5.8 shows functional block diagram of LMD18200 whereas table 5.7 summarizes logic truth table.

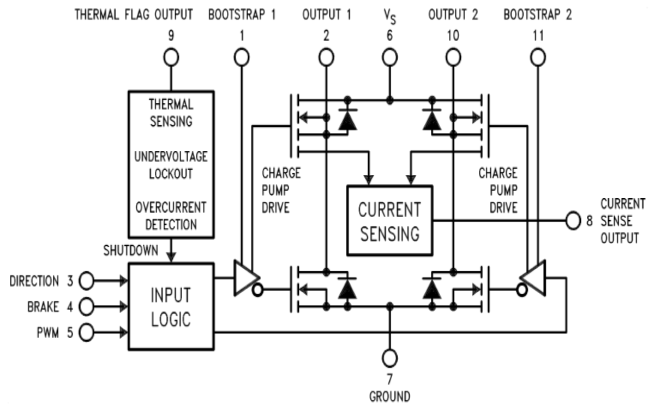


Fig. 5.8 LMD18200 functional block diagram

Table 5.7 Logic truth table

PWM	Dir	Brake	Active Output Drivers
H	H	L	Source 1, Sink 2
H	L	L	Sink 1, Source 2
L	X	L	Source 1, Source 2
H	H	H	Source 1, Source 2
H	L	H	Sink 1, Sink 2
L	X	H	NONE

The current sense output of LMD18200 has a sensitivity of 377 µA per ampere of output current. The current sense signal is noisy, even when filtered. With low currents the measurements can't be very much trusted. The speed of the motor can be controlled by raw PWM ratio or by setting the parameters of a PID controller and giving a speed request. The direction is always controlled by one bit. Detail of control algorithm has been explained in software architecture section.

To explain the operation of 1st stage of DCHH properly, schematics of a single sensor and comparator are shown in figure 5.9.

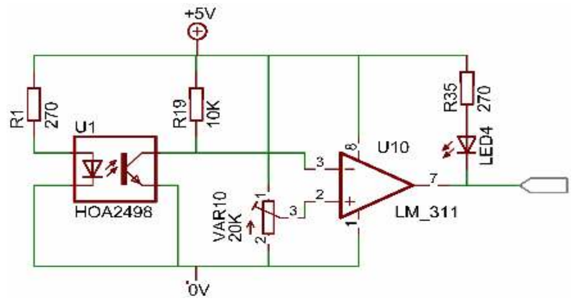


Fig. 5.9 Sensor interfaced comparator circuit

When significant IR falls on the base of RX transistor, then base-emitter junction is forward biases and hence base current flows into the transistor. Since, bipolar transistor is modelled as controlled current source; therefore base current causes the transistor to turn ‘on’ and thus collector current flows. On the other hand, if IR does not fall on the RX transistor, the transistor remains ‘off’ and no collector current flows. This property of the sensor has been used to form a potential divider. The potential at pin ‘3’ (inverting input) is Rsensor / (Rsensor + R19). Again, a good sensor circuit should give maximum change in potential on pin ‘3’ for no-light and bright-light conditions. This is especially important if a comparator is used as ADC. In present situation, the comparator has been used as a simple analog to digital converter to create a digital signal to be sent to the control stage of the rover. The other input of the comparator is connected to a 20 K variable resistor. Its purpose is to set the threshold triggering level. The comparator compares these two inputs and gives logic high at output if +ive input is greater than –ive voltage and vice versa. So, if the sensor detects the tether, the output of the comparator is at logic low and hence the LED is on, thus giving a digital value. The controller reads the data from the front-end in frame structure shown in figure 5.10.

L2	L1	C	R1	R2

Fig. 5.10 Sensor frame structure

Where

C = Centre

R1 = Right 1

R2 = Right 2

L1 = Left 1

L2 = Left 2

This rearrangement is done to make algorithm implementation easy. New values are then sent to onboard computer. OBC interprets this data and uses the information to control the locomotion motors. In this way, the robot continuously follows the tether. Selection of comparator was quite easy. Two options have been considered. Both of which work perfectly LM 311 and LM324. Although LM324 incorporates quad op-amps whereas LM311 is only a single op-amp but still LM 311 was chosen because these were readily available in large quantity.

Schematic of DCHH is shown in appendix A, whereas figure 5.11 shows the actual hardware snapshot.

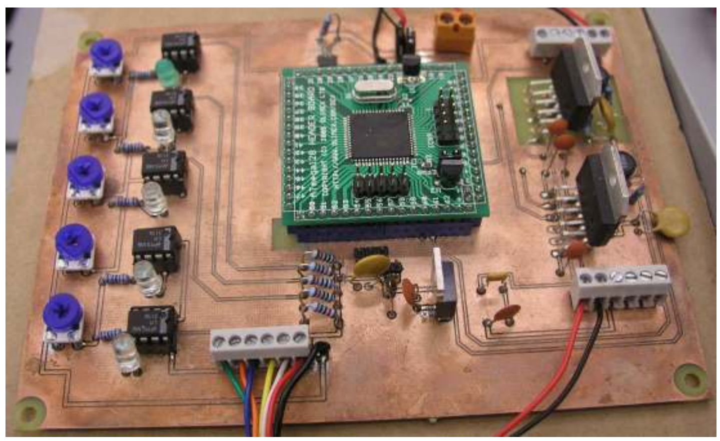


Fig. 5.11 DCHH

5.2 Communication architecture

This section briefly describes the data exchange among different parts of the system.

- **Remote Terminal ←→ C^{3}U**

Remote terminal simulates ground station. Communication between remote work station and C^{3}U has been done using Ethernet cable and WLAN. We have setup a USB based WLAN connection. For searching suitable WLAN transceiver, factors to be considered include USB version support, Linux version support, distance supported, availability and price. Following options have been considered: A-Link WL54USB has been chosen because of its Linux version compatibility, price and availability.

- **C^3U ←→ Tracks Mobility System**
- **C^3U ←→ DCHH**

Except front-end hardware, communication between all other entities is done using CAN protocol. CAN is a broadcast, differential serial bus standard for connecting electronic control units. CAN was specifically designed to be robust in electromagnetically noisy environments and can utilize a differential balanced line.

A PC104 compatible CAN interface card (AIM104) is integrated with the On-Board computer in C^3U for CAN Bus communication. PC/104 is a standard for PC-compatible modules (circuit boards) that can be stacked together to create an embedded computer system. PC/104 systems are very similar to standard desktop PCs but with a different form factor. The name "PC/104" is derived from this likeness and the special stackable bus connector having 104 pins. These systems can be programmed with the same development tools used with full-size PCs, which reduces the need and cost of custom development efforts. Although only about 104x104 mm2, PC/104 boards are very powerful for their size. PC/104 products are designed for minimal power consumption, small foot print, modularity, expandability and ruggedness.

On CAN, messages are identified by assigning unique ID to each message. The idea is that when using multiple motor controllers in the same bus, only the root microcontroller ID (mcid) has to be changed for each controller. Message IDs are then derived from the mcid. For example, motor controllers with ids of 0x20 and 0x40 receive pwm ratio instructions with message ids of 0x2E and 0x4E respectively. Thus the last number tells the type of the instruction and the second (and third, when used) tells which motor controller should receive the message. Thus to generalize if N is microcontroller specific ID (mcid), we have set following message IDs to implement mobility system and tether tracking system. (Table 5.8)

Table 5.8 CAN message for ROSA

Message	ID	Description
STOPALL	0x10	Stops all motors, global for all motor controllers
STATUS	0x14	Status message from a controller
COMMAND	0xN1	Command in data block (START, STOP)
SPEED	0xN3	Speed request for the PID controller
GET_SPEED	0xN4	Get motors current speed
ENCODER	0xN5	Set encoder ticks reading
GET_TICKS	0xN6	Get encoder ticks reading
GET_CURRENT	0xN7	Get motor current
GET_SENSOR	0xN8	Get IR Sensor Values
PID	0xNA	Set PID parameters
ACC	0xNC	Set acceleration
RAW	0xNE	Set raw PWM ratio (PID controller off)
ECHO	0xNF	Request echo

Global messages have IDs smaller than 0x20. Currently two are used. 0x10 sends a global stop command to all controllers in the CAN bus. 0x14 is global status message which can be send by any controller in the CAN bus. The first byte of the message tells who sent the message and remaining three tells the reason for the message.

- **Front End → DCHH**

Analog sensor data from front end is fed to DCHH through simple self-made connecting wires.

Overall communication architecture is shown in figure 5.12.

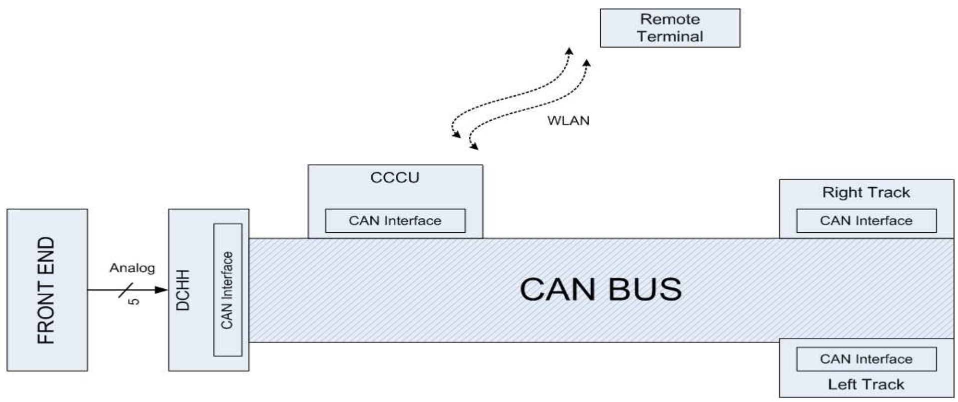


Fig. 5.12 Communication architecture

5.3 Algorithm development

As explained already, that DCHH sends sensor data to OBC of C^{3}U in following format through CAN interface. When sensor detects the tether beneath it, logic HIGH is fed to the controller. To extract tether position from this data set, we considered three algorithms. This section presents details of these algorithms.

L2	L1	C	R1	R2
LEFT		CENTER		RIGHT

Algorithm I:

If either R1 OR R2 == 1 → MOVE RIGHT

If either L1 OR L2 == 1 → MOVE LEFT

If (C== 1) → MOVE CENTRE (STRAIGHT)

If ALL = 0 → STAY AT PREVIOUS

Algorithm II:

This algorithm is quite obvious and has been kept in mind while designing the front end sensing system.

If R1 AND R2 == 1 → MOVE EXTREME RIGHT

If C AND R1 == 1 → MOVE RIGHT

If C ==1 → MOVE CENTRE (STRAIGHT)

If C AND L1 == 1 → MOVE LEFT

If l1 AND L2 == 1 → MOVE EXTREME LEFT

Algorithm III:

Step-I:

Read L, R & C where

L = Leftmost sensor which reads 1;

R= Rightmost sensor which reads 1.

If no sensor on Left (or Right) is 1 then L (or R) equals 1.

Example:

L2	L1	C	R1	R2
1	0	0	0	0

LEFT CENTER RIGHT

L=2 R=0

L2	L1	C	R1	R2
0	0	0	1	1

LEFT CENTER RIGHT

R=2 L=0

Step-II:

If all sensors read 0 go to step 3,

If (C= = 1) MOVE STRAIGHT

else,

If L>R MOVE LEFT

If L<R MOVE RIGHT

If L==R MOVE STRAIGHT

Go to step 4

Step-III:

Move clockwise if line was last seen on Right.

Move counter clockwise if line was last seen on Left.

Repeat step 3 till line is found.

Step-IV:

Go to step 1.

Because of narrow width of tether, there is no possibility that any of sensor from right and left becomes on simultaneously. Hence, this fact makes algorithm III unrealistic in case of ROSA.

When the rover moves, there are combinations when the tether comes under more than one sensor. Hence at least from theoretical point of view, 2nd algorithm seems to be realistic. But during implementation, it was found that the sensor can not be detect the tether even thought it is beneath the sensor. The reason is explained in detail in analysis section of chapter 5. Hence algorithm II is not practically feasible in all cases.

Since, speed of rover is neither high nor medium, hence a simple algorithm was supposed to work. Therefore, algorithm-I has been finally chosen.

5.4 Software architecture

This section presents software details of C^3U as well as microcontrollers of mobility system and DCHH. Tether tracking software has been developed by keeping existing wheel motor control software as a sample. To illustrate details of software architecture clearly, different command levels have been briefly explained first in this section. Then C^3U and microcontroller softwares are discussed.

5.4.1 Command levels

The ROSA rover code has been designed to support three different levels of command including.

- **High Level Commands:** Top level commands have been developed to control the mobility system and tether tracking system. For example, wind & unwind tether, drive, turn etc
- **Medium Level Commands:** Medium level commands give more control over the mobility system and tether tracking system. For example, wind tether by 60 cm.

- **Low Level Commands:** Low level commands include reading sensor values, setting different parameters like speed, acceleration, raw PWM, PID values and getting different parameters like speed, ticks, current etc

Most of the commands have been implemented at low level. Some commands like follow the tether is a high level command that uses combination of low level commands. The command levels are shown in block diagram in figure 5.13.

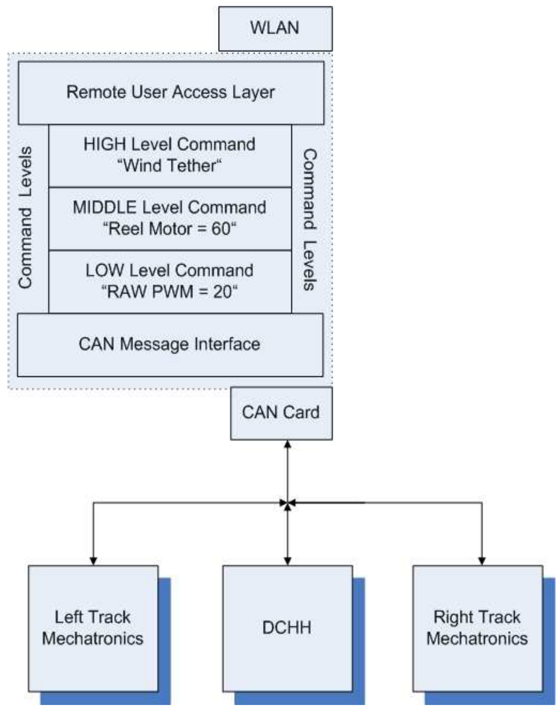


Fig. 5.13 Command level structure

5.4.2 C^3U software

The software on C^3U has been organized in well defined structure. After initialization, device is first opened followed by CAN reset. The control has possibility to exit if either of these steps is not successful. Since there are three microcontrollers in the system, therefore the control prompts for MCID. Finally it prompts for number/alphabet corresponding to low level command. These options are summarized in table 5.9.

Table 5.9 User interface

Option	Description
1	Set Speed
2	Get Speed
3	Get Current
4	Get Ticks
5	Set Acceleration
6	Set PWM
s	Get Sensor
q	Quit

Figure 5.14 shows flow chart of software. All the 'Get' commands are combined. Similarly all the 'Set' commands are shown as one branch for simplicity although all of these commands have unique message IDs.

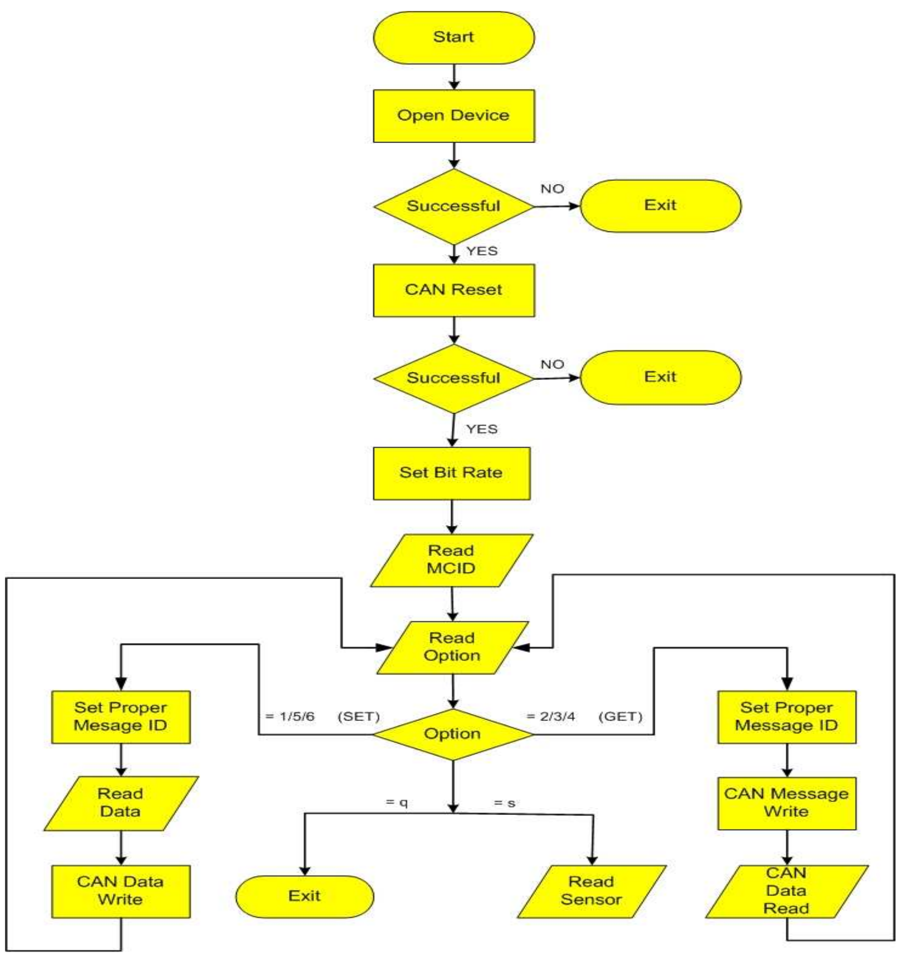


Fig. 5.14 Structure of C^3U code

5.4.3 Microcontroller software

When microcontrollers get these low level commands from C^3U via CAN, it needs to activate proper software sections to execute command. These software sections include Timer, Counter, ADC, PWM, CAN management, PID controller and Main. During initialization, ports, controller, CAN, counter, timers, PWM and ADC have been initialized. After the initialization, the controller starts an endless main loop. The main loop only checks if there are any new messages in the message buffer and handles the message specific requests. All the other actions are executed by interrupts. Higher level structure of microcontroller codes for mobility system and tether tracking system is illustrated in figure 5.15. Where as lower level software signal flow diagram of microcontroller code is shown in figure 5.16.

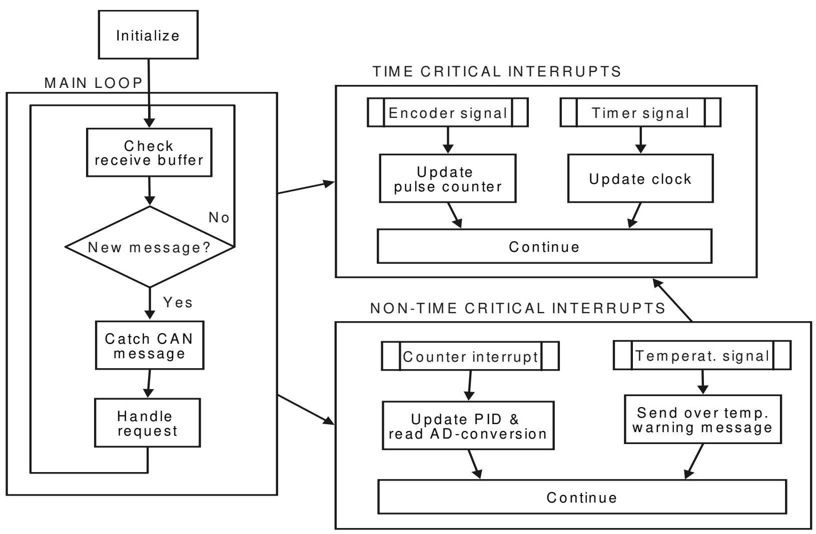


Fig. 5.15 Structure of microcontroller code

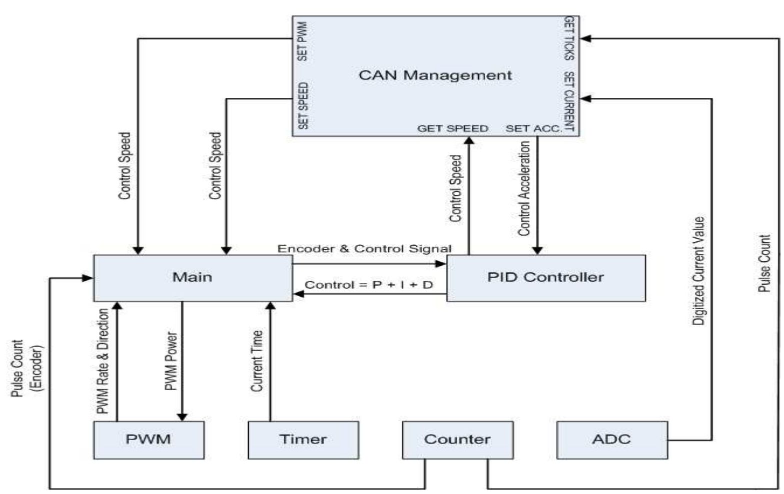


Fig. 5.16 Signal flow diagram of microcontroller code

Motors can be commanded by two options: Raw PWM values or by setting PID controller parameters. Control timer (Timer 2) has been used to check which of these should be used to command motors. Flow chart of control timer is shown in figure 5.17.

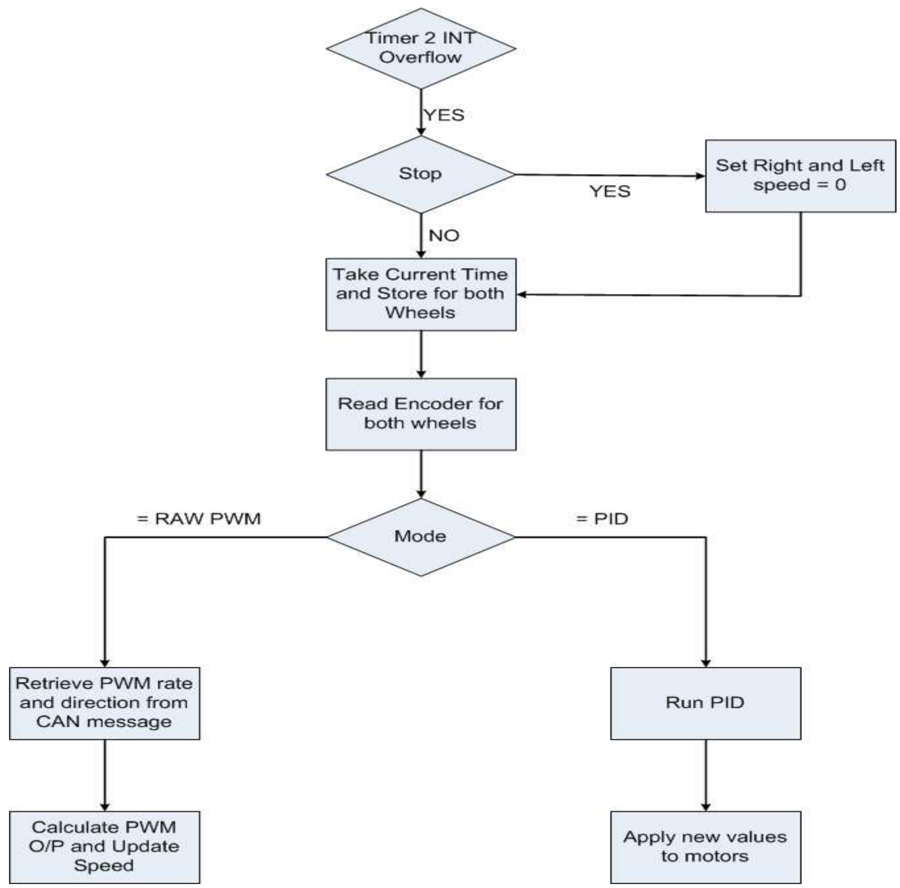


Fig. 5.17 Control timer flow chart

Chapter 6

Results and analysis

The first section describes testing setup details followed by results in the second section. Critical analysis of these results has been presented in next section. Finally, a review of the system and improvements are discussed in detail.

6.1 Testing

Testing background and purpose of each test has been explained in this section. This section explains details about these testing procedures at subsection level as well as testing of overall systems.

6.1.1 Mobility system testing

Already available hardware of mobility system has been thoroughly tested. The purpose of this test is to confirm the functionality of hardware, which can support tether tracking system implementation. In this test, the basic commands of rover have been verified. These include Back, Forth and Turn. This has been tested by giving PWM values of different magnitude and polarity to the locomotion motors. A second test of the mobility system is done by setting parameters of the track hardware and send back to check system response.

6.1.2 Tether tracking system subsection testing

Before testing the overall system as a whole, several tests at subsection level have been performed. The purpose of these subsection tests during the implementation phase is to facilitate overall testing of whole system. This has been done by isolating the subsection from rest of the system, giving a pseudo-input and critically analyze the results of that particular subsection. This subsection level testing proved to play an important role toward optimum system response. These tests include:

i. **IR sensor test:**

IR sensor should have enough sensitivity to detect reflections from the tether. Response of sensor against white (100% reflectance) and black (0% reflectance) surfaces has been tested prior to testing with tether. This has been done by constructing the sensor circuit. The sensor has been put in such a way that its RX and TX are facing the reflective surface. The voltage at different heights above the tether has been measured and the height the sensor needs to be above the tether to be accurate enough has been determined. For this pre-prototyping, bread board has been used as implementation platform.

ii. **Front end assembly verification test:**

Initially card board front end assemblies have been attached with the rover at different locations. Rover is moved in possible directions and presence of tether under different sensor holes has observed visually.

iii. **CAN transceiver functionality test:**

To test functionality of CAN transceiver and controller subsection, CAN is connected with the controller at any IO port pins (Port D6 and Port D7 in our case). A simple code to turn on the LED from remote computer is written to verify functionality of CAN.

iv. **Motor drivers test:**

Motor drivers for reel and feed motors have been intensively tested after designing. This has been done by connecting motor drivers at IO ports of controller (PortB14 and PortB16 in our case). Two motors have been connected at corresponding M+ and M- terminals of motor drivers. These motor have been then commanded from the remote terminal via CAN. PWM values from the remote station have been varied to record PWM outputs and observe speed variation of motors visually. The same testing process has been repeated for negative direction.

v. Comparator section operation test:

The purpose of this test is to observe the behavior of the comparator subsection in response to pseudo-inputs. Different voltages from the power supply are given to inverting and non-inverting inputs of opamps and output is monitored using multimeter.

vi. Sensor data read test:

This is the last test before the testing tether tracking system as a whole. It verifies proper integration of front-end and DCHH. From the sensor frame structure (fig. 5.10), we know what we should get when any of sensor (s) is/are 'on'. For example, when the tether is at centre, we should get 000 <u>00 1 00</u> (= 4). When tether is at right, we should get 000 <u>00 0 10</u> (=2) or 000 <u>00 0 01</u> (=1).

For this test, the rover was at rest. The tether has been manually moved in all possible directions to get different combinations of 'on' sensor (s). Data from the sensor has been read on remote terminal and compared with what we should get as per actual frame structure. In this way, integration of both hardwares of the tether tracking system has been tested.

6.1.3 Tether tracking system testing

The purpose of this test is to confirm functionality of the tether tracking hardware and to find the accuracy of system. The tether has been spread in different patterns on the test platform. Both sides of the tether track have been taped. This corresponds to actual tether position. The rover is then commanded to move and follow the tether from the remote terminal. A pointer has been attached with the rover to get ground truth that is actually followed by the rover. Figure 6.1 shows ROSA during testing phase.

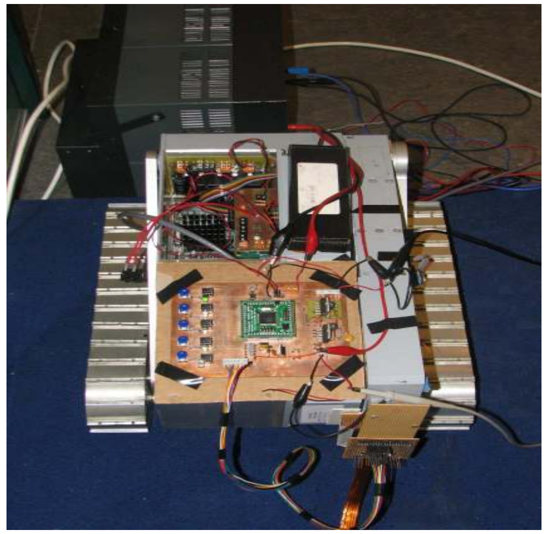


Fig. 6.1 ROSA during testing

A big wooden carpeted block has been used as test platform. The dimensions of the platform were 2 X 1.22 m. Figure 6.2 shows the testing platform having different tracks marked.

Fig. 6.2 Testing Platform

6.2 Results

This section includes results for the mobility system and the tether tracking system on subsection level as well as complete system.

6.2.1 Mobility system testing

The hardware of both tracks is symmetrical. Hence results of single (left) track are presented. Figure 6.3 and 6.4 shows motor drive signals for PWM inputs of 50 and 250 respectively. Test results for the mobility system parameters have been tabulated in table 6.1.

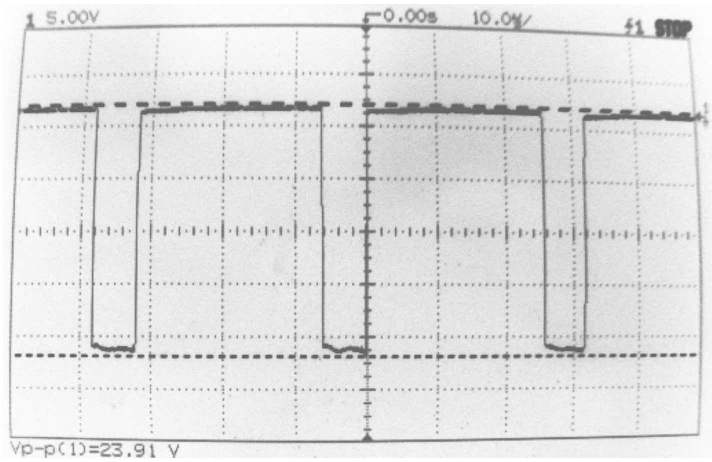


Fig. 6.3 Left locomotion motor driver waveform PWM = 50

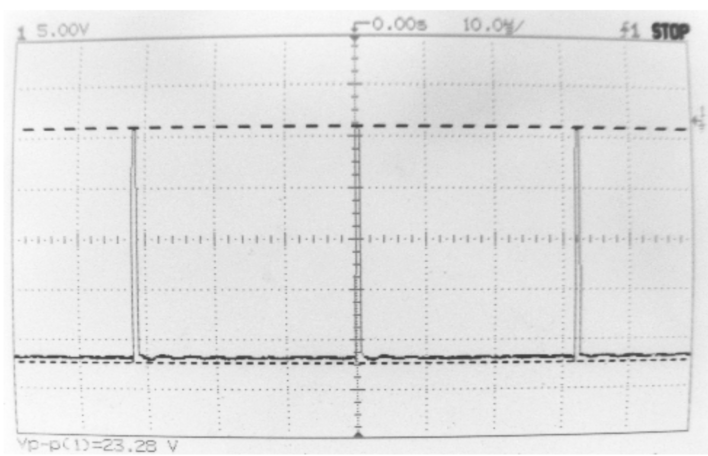


Fig. 6.4 Left locomotion motor driver waveform PWM = 250

Table 6.1 Mobility system test results

Direction	Set Speed (tps)		Speed Achieved (tps)		Current Achieved (mA)	
	Right	Left	Right	Left	Right	Left
Backward	200	200	184 → 214	184 → 214	73	72
Forward	-200	-200	-178→ -208	-178→ -208	75	73
Right	200	-200	195→ 218	-179 → -218	95	60
Left	-200	200	-192 → -231	189→ 216	62	92

6.2.2 Tether tracking system subsection testing

i. IR sensor test:

Let d = Distance between sensor and reflective surface.

As a result of experimentation, maximum, minimum and optimum (d_{op}) point of response to detect IR reflections from the tether has been found as

d_{min} = 2.5 mm

d_{op} = 5.5 mm

d_{max} = 1.0 cm

ii. Front end assembly verification test

Results of this part include finalization of front end assembly design. Zig zag assembly has been finally selected (fig. 5.2). The second outcome of this part was proper mounting position of front end assembly on the rover. Front end assembly has been mounted perpendicular to the ground surface. Rover is moved in different directions and presence of tether under different sensor holes has been confirmed visually.

iii. CAN transceiver functionality test

By writing a simple code to turn the LED on/off from the remote computer, provided a straightforward way to check connection between the remote computer and C^3U, CAN card operation, functionality of CAN transceiver of the DCHH and microcontroller IO port. Every thing worked fine after fixing some errors.

iv. Motor drivers test

Figure 6.5 shows motor drive signals for reel and feed motors for equal PWM values (100). The output signal corresponding to half PWM ratios is shown in figure 6.6. The direction of attached motors has been visually observed and polarity of positive and negative PWMs has been confirmed.

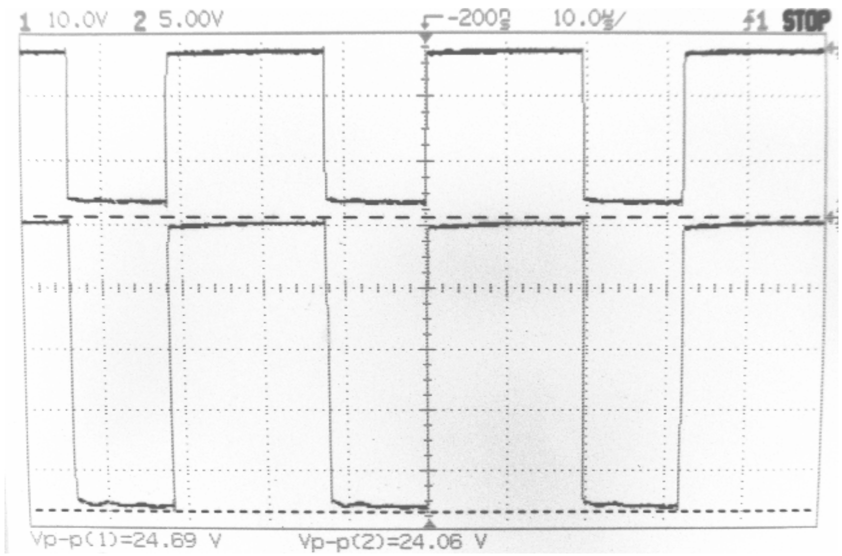


Fig. 6.5 Motor drive waveforms PWM reel motor = PWM feed motor = 100

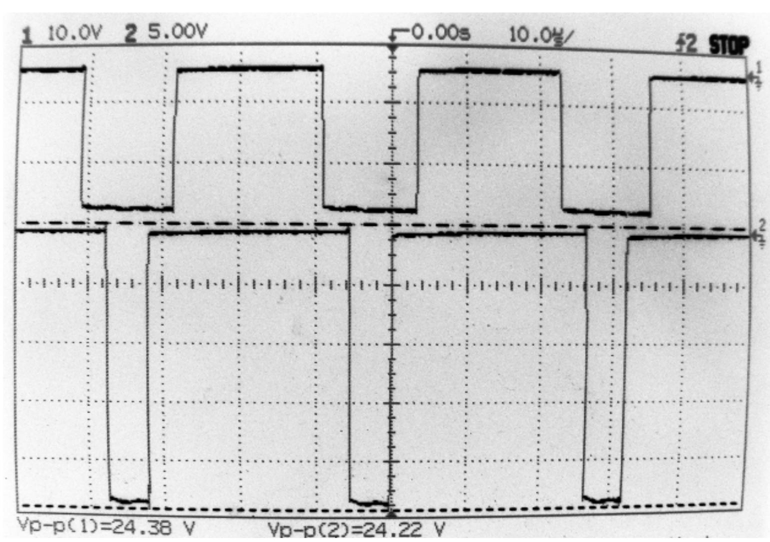


Fig. 6.6 Motor drive waveforms PWM reel motor = 100, PWM feed motor = 50

v. Comparator section operation test

Results of this subsection are shown in table 6.2.

Table 6.2 Comparator section operation test results

Non-inverting Pin V+	Inverting Pin V-	Output
2V	GND	4.92V
GND	2V	0.02V
3V	1V	4.9V
1V	3V	0.03V

vi. Sensor data read test

Figure 6.7 shows user interface at the remote terminal as well as test results for a case where the tether is moved from centre to extreme right. Initially, the tether is in centre position, we got 4 at the user interface. Then the tether is moved right, we got 2 and finally when the tether is moved more right, we got 1 at the user-interface. If we compare it with the example in test section, it is obvious that

Data obtained at the user terminal = Theoretical sensor data (as per frame structure)

Similarly, table 6.3 shows all other possible sensor data combinations.

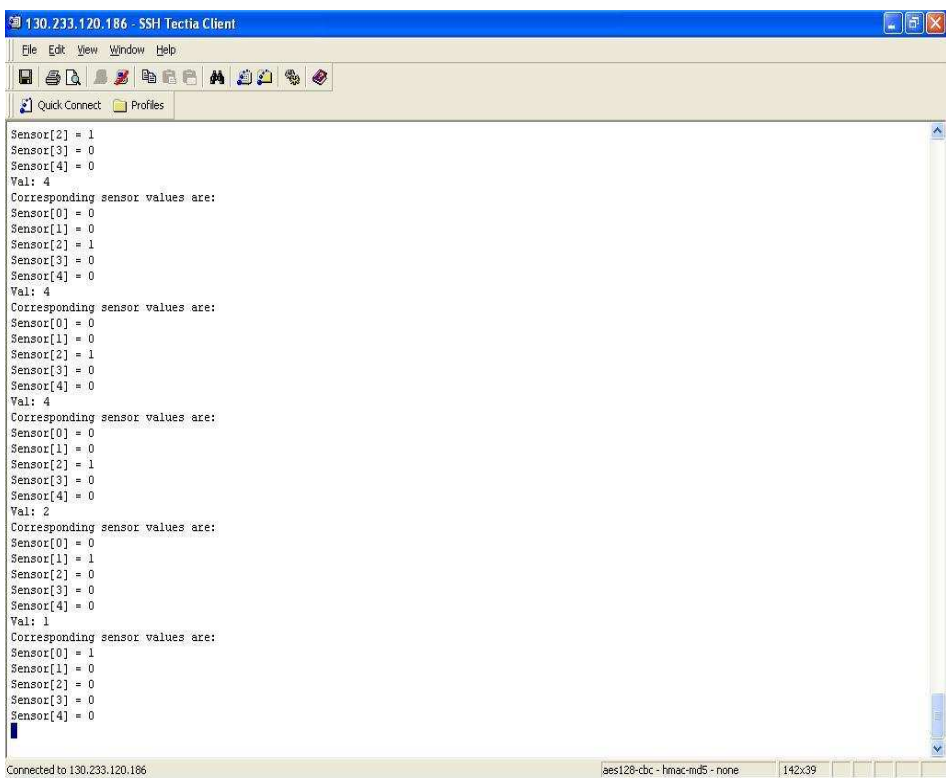


Fig. 6.7 Sensors data at user interface when tether moves from centre to right

Table 6.3 Sensor data read test results

ON Sensor (s)	Received Sensor Data (Binary)	Received Sensor Data (Decimal)
C	000 00100	4
R1	000 00010	2
R2	000 00001	1
L1	000 01000	8
L2	000 10000	16
C+R1	000 00110	6
R1+R2	000 00011	3
C+L1	000 01100	12
L1+L2	000 11000	24

6.2.3 Tether tracking system results

Results of the tether tracking system are presented from figure 6.8 to figure 6.11. Green line shows actual position of the tether whereas bluish circles represent tracked positions of the rover.

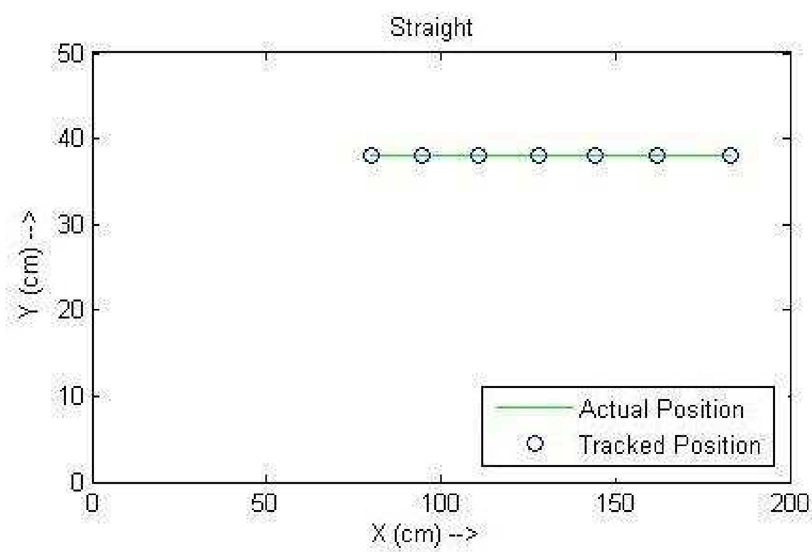


Fig. 6.8 Tether tracking graph (Straight)

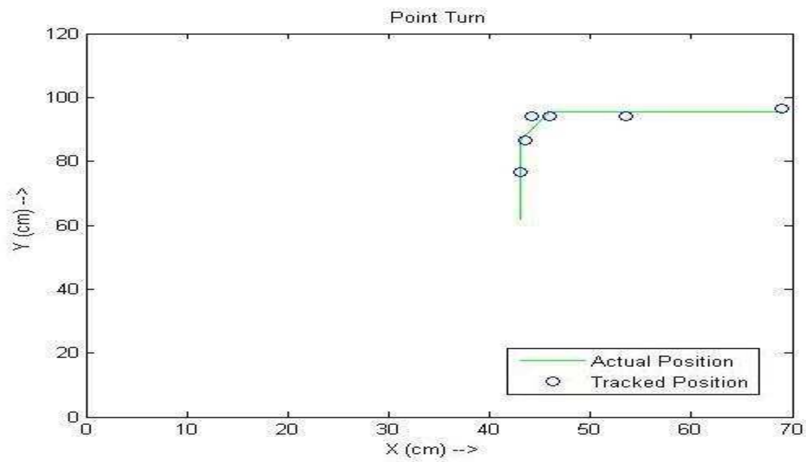


Fig. 6.9 Tether tracking graph (Point turn)

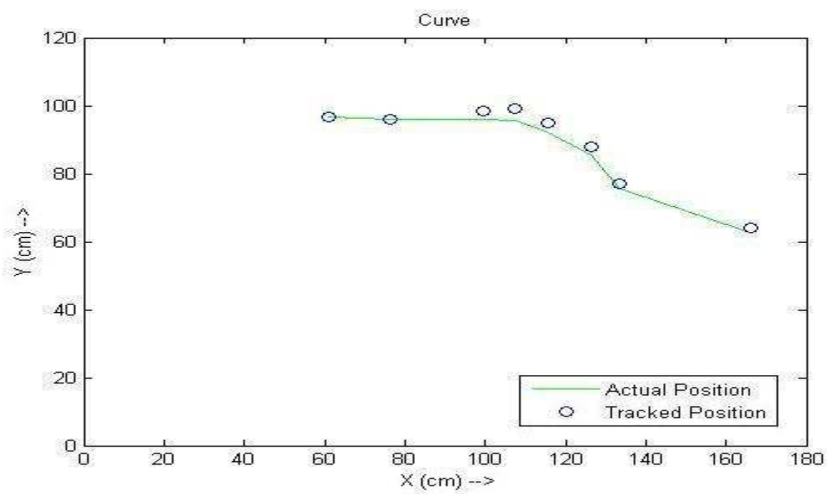


Fig. 6.10 Tether tracking graph (Curve)

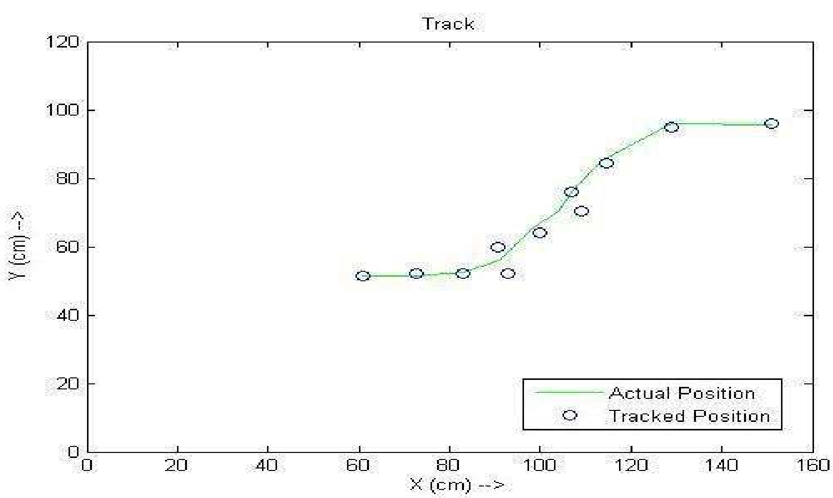


Fig. 6.11 Tether tracking graph (Track)

6.3 Analysis

Results obtained from testing of the IR sensor are quite close to specifications given by the data sheet (optimum d = 6.35 mm). Value of d_{max} (1.0 cm) is much less than mentioned in the data sheet (1.5 cm). This is because of bad reflection coefficient of the tether as compared to white. In any case, mounting of the sensor assembly has been done in a way that this reflectance distance (d) does not remain a crucial factor. Results of the front-end assembly helped to finalize an optimum assembly as zig-zag. Results of the CAN test showed that CAN can handle differential signals well. Results of the sensor reading subsection revealed that for all combinations of 'on' sensors, readily available data at user interface is as per frame structure. Similarly results obtained from other subsections are also as per expectations.

During testing of the mobility system, it was observed that some times the feedback loop of the control system does not work accurately. Even difference in 'set speed' and 'speed achieved' values more than 15% has been noticed. Since the variation is not negligible and it is random and can be of either polarity, hence it is quite foreseen that averaging/standard deviation would not give accurate results. Overall the mobility system of the rover provided a good platform for testing and implementing the tether tracking control system.

Waveform results of the tether motor driver show that output voltage signal has ripple but it is too small (<1V) to effect operation of motors. The waveforms of reel and feed motors clearly show that DCHH is capable of controlling the speed of both motors independently. The DCHH also provides facility to control the speed of both motors by giving speed value as input rather than PWM ratio.

Results of the straight tether tracking system show that the rover follows straight path exactly. That was quite obvious outcome. The straight tether tracking provided an easy way to calibrate the system.

Results of point turn and curve show that there are some errors associated with tracked line especially in the vicinity of turn. The differences between actual and tracked paths increase if the track has continuous turns (fig. 6.11). The developed system is capable of tracking the tether within ± 6 cm. The errors have been intensively analyzed by using several geometrical placement of tether and letting the rover track it. Reasons for these errors and problems associated in tether tracking system are summarized below:

- The color of tether is yellowish orange (no justification present in documentation). We have proposed and implemented tether tracking system based on IR sensing, so amount of reflections from the target surface do matter a lot. The tether tracking system is expected to give far better response if tether is painted with white (having reflectance coefficient = 100% or 1).
- The 2nd challenge which we have faced is that unfortunately even the yellowish orange tether is not 100% reflective. The tether has 5 conductors in it. Reflections can be detected from these conductors. But there are 6 parts (insulators) in tether that are transparent and do not give any response to IR incident rays (fig. 6.12). This increases the miss rate and thus increased non-linearity. Unfortunately, both corners of tether are transparent. So during the motion of rover, when tether enters into next sensor region, reflections from TX are passed through the tether and thus RX does not receive IR echoes. Hence the front end misses the tether, even though it is beneath that sensor.

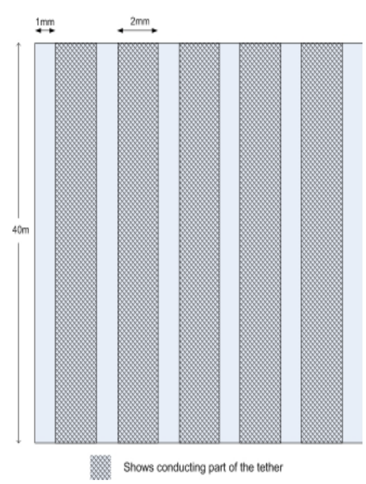


Fig. 6.12 Tether composition

- Apart from corners, the same problem arises when transparent part of the tether is under transmitter of IR sensor. This is quite often because the beam of sensor is very focused and concentrated in a specific region. So, even if the whole tether is under the sensor, it can not detect the tether. All of the above problems can be solved by painting tether with white.

- When the rover moves, due to the tether tension, length of the tether near rover is displaced. Hence actual position of the rover is already changed before the rover comes on that point. The rover always follows the tether but the problem is that tether is no more at its original position. Hence, error rate is increased. This is one of reason because of which the turn radius is not constant. Different tension, orientation, speed and acceleration cause different turn radius.
- In the current system, tether winding and unwinding is semi-autonomous. User can command both reel and feed motors directly from remote terminal. It has been observed that the tether winding at proper time has also great influence on results. Since sensors are mounted very close to one another, so if the tether is loose then it might come beneath some other neighbor sensor thus effecting the tether tracking system results. Hence, sophisticated tension measurement system would definitely improve accuracy of the system. Two methods have been proposed in section of future work in next chapter.

6.4 System design review

This section gives critical sight on system from electrical as well as mechanical aspects. Solutions have also been recommended.

1) **Reducing power consumption:** During operation power is almost continuously supplied to the rover from the lander. Hence power consumption becomes a critical issue. The power losses on the tether can be decreased by using relatively high (e.g.100 V) transfer voltage. This arrangement requires two high efficiency DC/DC converters, one for lifting the voltage level up to 100 V on the lander side and one for decreasing the voltage back to the usable level on the rover side.

2) **Ambient noise catering mechanism:** IR sensors have main problem that these are not very immune to ambient noise. In the proposed design, the color of front end and mounting of the sensors make it sure that there is no effect of the ambient

light. So, ambient noise catering mechanism is not there in hardware. However, it can be implemented by one of two solutions:

- **Using On-chip ADC**

The microcontroller starts to scan the sensor status, sample an output voltage, turn on LED and sample again the output voltage. The difference between the two samples is the optical current by LED (fig. 6.13). Thus the output voltage introduced by the ambient light is canceled. The other sensors are also scanned in the same way in sequence. Block diagram of such hardware system is shown in figure 6.14.

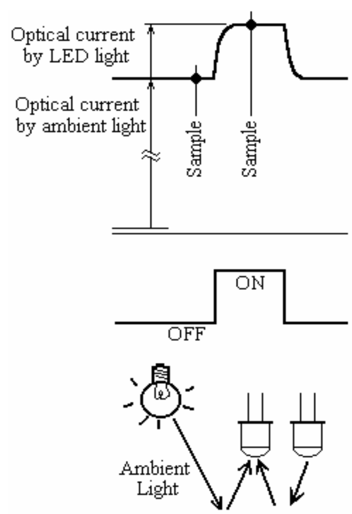


Fig. 6.13 IR operation: Ambient noise

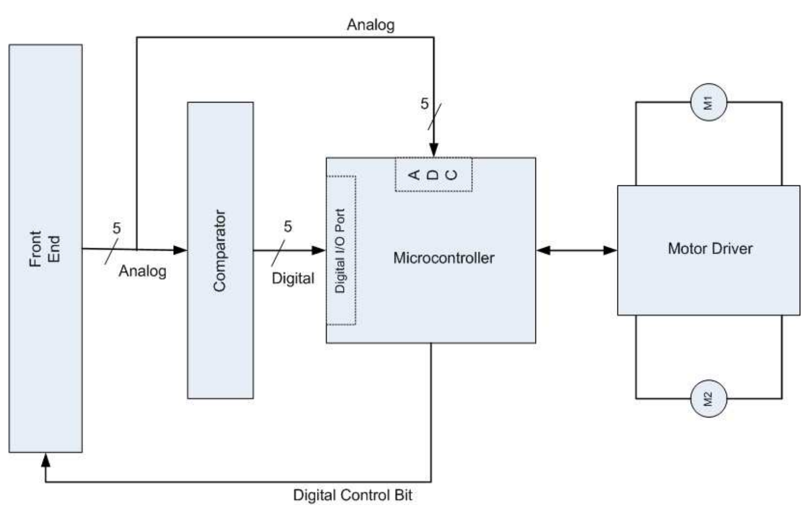


Fig. 6.14 Ambient noise reduction using ADCs

- **Using modulator & demodulator**

The second and more straightforward approach to cater the ambient noise is by modulation and demodulation. Using modulation, we make the IR light source blink with a particular frequency. The IR receiver will be tuned to that frequency, so it can ignore everything else. Figure 6.15 shows the simplified block diagram of ambient noise reduction using modulator/demodulator.

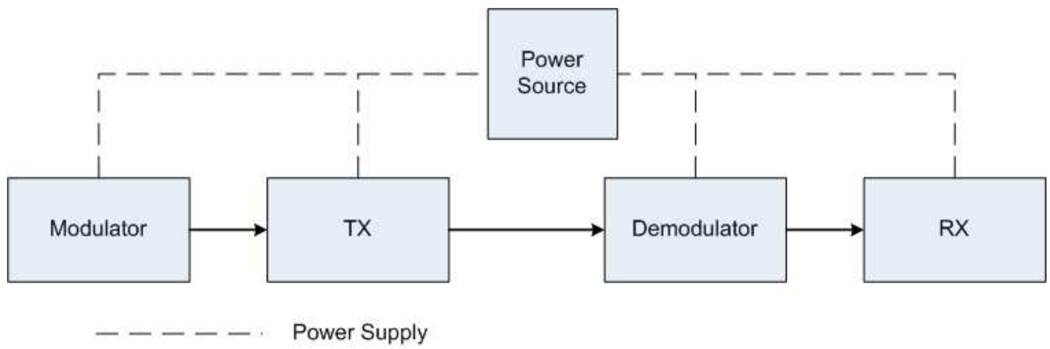


Fig. 6.15 Ambient noise reduction using mod/demod

Another option is to use a modulated Infrared Reflective Detector (single ASIC). For example – Mondotronics 3-337 is IR sensor having built in modulator/demodulator.

3) **Increasing reliability:** The control of tether motors require much more accuracy than the control of the traction motors. Their direction information is very valuable. In order to further increase reliability, the encoder pulses of tether motors can be first fed to an encoder signal converter unit rather than connecting these pulses directly to the controller. This encoder signal converter converts the two encoder pulse channels to one single channel and to a digital signal indicating the direction. Proposed schematics can be like that of figure 6.16.

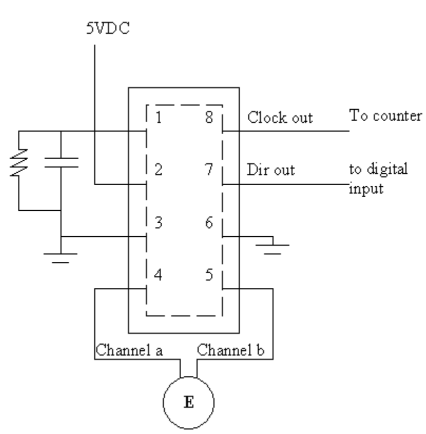


Fig. 6.16 Encoder signal converter unit

Chapter 7

Conclusion and future work

Tethered rovers provide lot of advantages as well as big challenges for space missions. A tether acts as a communication channel as well as medium for power transfer. The challenges associated with the tethered rovers include sophisticated control, tether management and increased failure risk. A concept of tether control system has been proposed. The system has been developed on architectural level and to realize the concept, design and development have been done on component level. The developed system is capable of tracking the tether within resolution of ± 6 cm. Since tether of ROSA is very flexible, so this resolution is quite enough. To further increase accuracy of proposed system, the tether tension measurement sensor could be installed at tether-rover join point. This tether tension measurement sensor provides the information when to wind the tether. Hence, the proposed system together with angle/pressure sensor seems to be a perfect system for tether tracking. Suggestions to improve the design and milestone for future work have been proposed.

The greatest challenge while designing and implementing the system was recommendation by lab staff, not to alter any mechanical/electrical or any other characteristic of ROSA. Even I am not allowed to paint the color of tether as white, which of course would had made results more accurate and system implementation more simpler. Secondly, mounting could have been more easy and better if I would have been allowed to make drills inside ROSA. So, this prototype involved 0% change in any aspect of existing ROSA. The prototype has revealed the challenges associated with the tethered robotics. The proposed system can be used in wide variety of tethered robotic applications ranging from underwater to space.

7.1 Future work

Research and development area of tethered rovers is interesting and hot field. It would be nice to keep following possibilities in mind while planning for future.

1. **Algorithm development:** The negative side of the tether is its tendency to catch obstacles. Considering planetary environment, these obstacles might be rocks or a huge block of soil possibility resulted from storm. Hence, tether tracking and control algorithms having reduced probability of entanglement needs to be developed. The developed algorithms can then be implemented using embedded hardware like FPGA/ signal processor/embedded controller.

2. **Space qualified rover:** After the rover requirements are agreed on, the next step would be to design a space qualified rover. The Martian environment has special features that need to be analyzed. For example the effects of the wide temperature range, vacuum, low gravity, and abundance of fine dust need to be analyzed.

3. **Navigation system**: Since ROSA is teleoperated, the positioning of the rover is required. Possible strategies for navigation include development of a system based on a video camera and LEDs in the corners of the rover. By blinking the LEDs and analyzing the video image, the position of the rover can be determined.

4. **Intelligent path planning**: Path planning is very critical in case of tethered rovers because improper path planning might lead to a situation where tether is entangled.

5. **Wireless communication:** The tether causes the most critical risk in the system. The length of the tether is more than what is usually used with the serial communication. The tether may also be entangled which may affect the communication. Thus, it would have been an interesting option to use wireless communication

6. **Subsystems level future work:** To facilitate the operation of rover, following work can be done on subsystem level:

- **DSS:** As explained previously, ROSA is not equipped with drilling and sampling instruments, so a good exercise for future would be to design and develop DSS which should be capable for subsurface sampling.
- **Tether reel length measurement:** Both tether motors have been already equipped with encoders. The encoder of motor pulling the tether, together with the encoders of mobility system (already integrated) can be used to determine the ratio of tether reeling speed and roving speed. The encoder of reel motor can be used to monitor the actual rotation speed of the motor. The ratio of pulses from encoders can be used to determine the length of tether still on the reel. This is a very useful feature especially if the C^3U accidentally reboots.
- **Tether tension measurement:** To prevent the tether from damage, the operator must always be aware of tension of tether or at least be informed when the tension is getting too high. Secondly as discussed earlier, to have more accuracy in tether tracking mechanism, tether tension should be measured. The tension of the tether can be determined by:
    - i. Analog force/pressure sensor: This method requires complicated mechanism but it is reliable. Futek FBB300 force transducer can be considered.
    - ii. Metal switches: Outlet of the tether can be equipped with two thin metal plates working as a spring. In this configuration, the tether can be routed out between these plates. Moreover four micro switches surround the outlet. Thus, if the tether is untensioned the spring is also untensioned and none of the micro switches is active. If the tether gets stuck, one or two of these micro switches activate and the operator is informed of the increased tension and also of the direction of the tether. [Petteri]
- **PWM control of lift and tilt motors:** Motors for lift and tilt motors can be controlled by PWM using same strategy as proposed hardware.
- **Pitching angle measurement:** To measure the pitching angle, the pitching joint can be equipped with an angle sensor. The lifting motor can also be quipped with a similar sensor to determine the height of payload cab.

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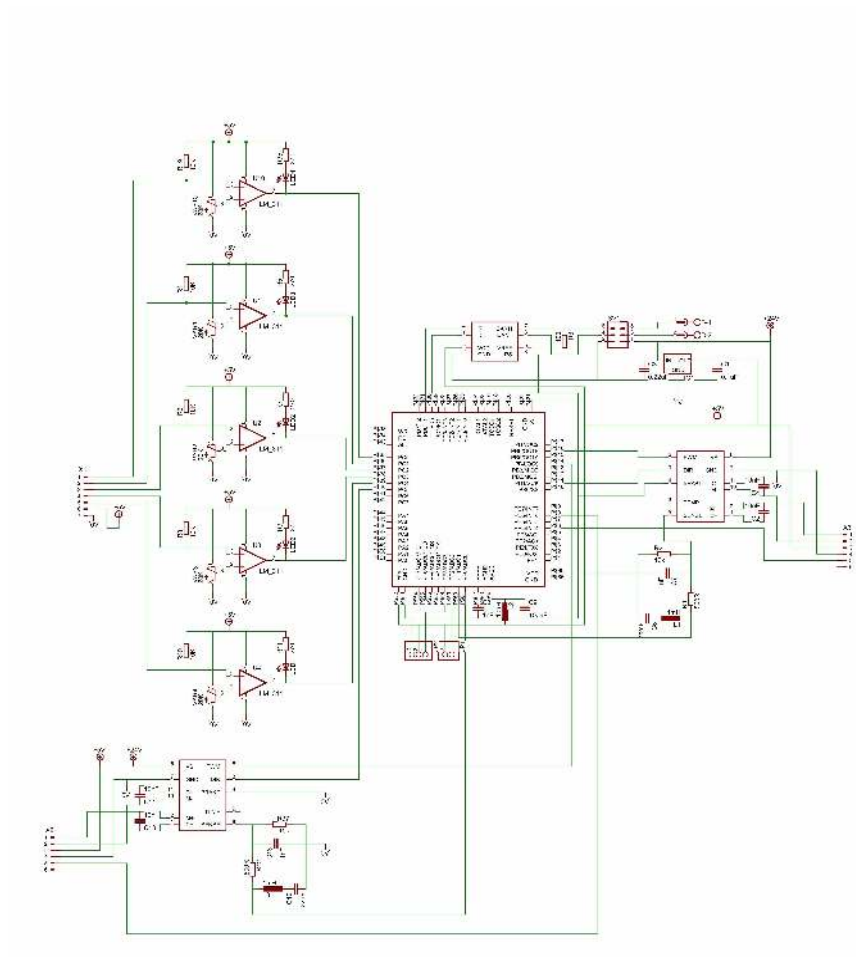
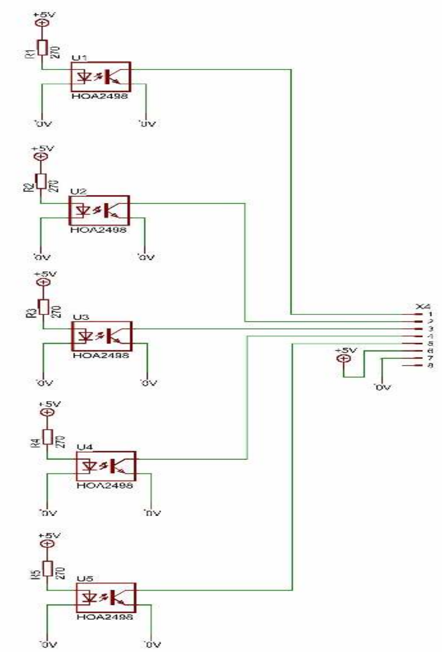
Appendix A



DCHH schematics



Front end schematics