Development of a limbs/wheels robot for planetary exploration.

Internship Report

“The man with a new idea is a crank until the idea succeeds.”
- Mark Twain

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To
Dr. Yoshiki Morino
Dr. Kazuya Yoshida

By Alexandre Fréchette
Acknowledgements

“Education is a progressive discovery of our own ignorance.” - Will Durant, American historian

Within all projects there are always challenges that could not be overcome without the help of knowledgeable advisors. Throughout this short term internship of three months I was fortunate enough to be accompanied by such competent professors and researchers. I am indebted to many individuals for acting as guides and mentors throughout this internship.

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Alexandre Frechette Bsc
Ecole Polytechnique de Montreal
Mec Eng
Sendai – 10th August, 2007

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Abstract

The topic selected for this internship was to work on the development of a limbs/wheels robot for planetary exploration. This report goes over the reasons behind the development of this platform, the concept, the fabrication steps and problems encountered as well as the solutions that were used or planned to be used in the future. The final research applications for the robot named LEON - Lunar Exploration Omnidirectional Netbot are also mentioned. The development method required to use and improve mechanical, electrical and software skills. In the end, the limbs part of the robot was operational in open-loop and remote control. The wheel design has reached maturity and an hybrid approach for the communication was finally selected to prevent problem with RS485 conversion and timing. The implementation of the wheel was still to be done as well as the integration of environmental sensors.
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## List of Acronyms

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<th>Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>LEON</td>
<td>Lunar Exploration Omnidirectional Netbot</td>
</tr>
<tr>
<td>LRF</td>
<td>Laser Range Finder</td>
</tr>
<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
</tr>
</tbody>
</table>
"Space isn’t remote at all. It’s only an hour’s drive away if your car could go straight upwards." - Sir Fred Hoyle.

It would also be easier if solutions were found following a straight path. But although wheeled vehicles have been improved since the discovery of the wheel several thousand years ago; they operate much better on paved surfaces than on natural surface. Uneven terrains with low bearing capacity represent a great challenge especially for wheeled locomotion vehicles. This explains why humans substantially paved areas of the world solely for the convenience of using such mean of locomotion. In 1967, it was evaluated that half of the Earth’s land surface was still inaccessible for wheeled or tracked vehicles. [Song & Waldron, 1989] Moreover, according to Bekker study [1960], walking machines would be more efficient than tracked or wheeled vehicles on a soft ground composed of 10-in. layer of plastic soil. Walking machines would also have greater speed, better fuel economy, greater mobility, better isolation from terrain irregularities and less environmental damage in harsh terrain conditions. [Song & Waldron, 1989]

Nevertheless, only recent progresses in computers technology enable humanity to start designing controlled legged vehicles. For such reasons, research over the past decades has been made to improve knowledge of walking vehicles. Although, legged vehicles were seriously investigated in the early 1960’s for concept of legged locomotion for a lunar rover; wheeled vehicles were however preferred for lunar and Mars missions due to their increased reliability and efficiency on flat surface. But in order to extract the full science potential of a planetary body, robots must be able to access its entire surface. And not only access the relatively level areas achieved so far. A hybrid solution with wheels and limbs would represent an ideal platform that offers the best efficiency, mobility and speed on all terrain. Moreover, in order to keep the pace in space exploration and research, productivity gains are necessary; for
this purpose reusability of components needs to be considered. Different exploration missions imply different conditions in term of time delay in the communication media and in term of environment for the mobile robot to operate (gravity, terrain roughness, etc.). Such system would also fit well in the desire of space agency to reduce cost between missions by offering a reusable platform. The ATHLETE rover designed by NASA JPL would be an example of development toward such hybrid concept. However A reusable platform to avoid redundancy in development and implementation phases needs to handle any kind of teleoperation, in any mission condition. Therefore a Versatile Modular Telerobotic platform for Planetary Exploration Mission is required.

The development and fabrication of such platform will be discussed throughout this report and will list the work that has been accomplished during the three months period of this internship at Tohoku University. The original concept of the platform that will be presented in the next chapters was developed by Dr. Eric Rohner. This platform will be used to perform his post doctorate research mainly focused on teleoperation.

The next chapter develop the main concept behind the platform. The fourth chapter is elaborating on the platform fabrication and its actual status. The final chapter discuss the platform potential for research.
“Space is the breath of art.” - Frank Lloyd Wright

They are many ways to create limbs/wheels robot and this chapter will present one that is original in many aspects. Such robot can be used with a Versatile Modular Telerobotic Platform for Planetary Exploration Missions.

Two main issues are not considered in past teleoperation research:

- increased time delay
- possible extreme gravity condition

The target platform based on the previous research [Rohmer, 2006a] needs to take into account those two issues. And allowing the use of any type of telerobotic to become versatile. Two missions to implement the platform were considered since they illustrate two opposite cases to demonstrate the versatility of the platform.

**Lunar H₂O prospecting at the Moon’s South Pole**

The mission:

For this lunar H₂O prospecting mission, a telerobotic platform is proposed based on cooperative hybrid robots to explore the pole’s craters. The robots’ degree of autonomy depends on the complexity of the mission (simple recognition, complex scientific measurement or sampling returns) and the operator site is either located on earth or in a lunar base. As the robots need to move on the strongly uneven surface of the crater, their design need to handle an appropriate grasp for their motion or to operate the lunar surface with some tools. Issues for the teleoperation platform:

- no gravity issue, but even sandy or uneven rocky terrain
- short time delays (about 3 s) allowing Manual Teleoperation from Earth or supervisory control
**Asteroid exploration (Hayabusa mark 2)**

The mission:

Asteroids are bodies without atmospheres that orbit the sun but are too small to be classified as planets. One of the main features of asteroids is the nearly complete absence of gravity. In microgravity environment, objects do not fall nor significantly attracted each other. Thus, the best method to achieve mobility on these small planetary bodies is still a subject of discussion and research [Chacin, 2006]. For the considered mission, a limbed robot will be located during the space trip in the main spacecraft that will be deployed on the asteroid surface to touch down on a boulder. The limbs will catch and grasp the surface of the asteroid and the locomotion will occur by continuously grasping further rocks on the surface (vertical rock climbing or hugging walk). The semi autonomous robot will be using an offline teleoperation as the time delay between the Earth and the asteroid are too long.

Issues for the teleoperation platform:

- microgravity
- long time delay (several minutes) implying supervisory control or offline teleoperation

This novel hybrid robot named LEON- Lunar Exploration Omnidirectional Netbot - is a hexapod that has two wheels. As shown in the previous example, the advantages of having six legs are heavily discussed in literature. [Song & Waldron, 1989] The concept has been widely tested and is considered by many space agencies for diverse applications. The main advantages of the hexapod encompass a good balance between stability, the possibility of manipulation of objects, the number of degrees of freedom as well as reliability and complexity of the system. One example of a hexapod developed by NASA is Lemur which is foreseen for space installation maintenance.
The hybrid robot discussed in this report has also two wheels dynamically balanced like nBot and Segway. The concept for a two-wheeled dynamically balancing robot is quite simple. The wheels are driven in the direction that the upper part of the robot is falling and will stay balanced as long as the wheels have sufficient control to remain under the robot's center of gravity.

But innovation of this robot not only relies on the fact that it is hybrid but mainly because the wheels are achieved by folding two opposite legs. Doing so reduces the overall weight of the robot while increasing the overall size of the wheel. Bigger wheels mean that the robot can go faster and can also go over larger objects. Folding the legs also has the advantage of lowering the center of gravity which reduces the likeliness of tipping over. The remaining two limbs can also be used as manipulator. The overall design will be discussed in this chapter covering the main components. The wheels/limbs will be described in more details.
2.1 Overall Design

In order to successfully accomplish its tasks the following versatile robot was developed. The figure below shows the robot in wheels mode and the following figure list the main components of the design. The components are separated in 4 groups: the environment sensors, the controls & communications, the power, motion & support and the limbs/wheels.

Figure 3: LEON in wheel mode.
Figure 4: Versatile platform design overview.
2.1.1 Proprioceptive and Exteroceptive Sensors

The webcam allows processing and transmitting images of the environment while the laser range finder enables the computer to reconstruct a 3D model of the environment in order to increase the autonomy degree of the hybrid robot (limb motion planning, path planning, autonomous wheel limb transformation). The webcam can provide information about the localization of the vehicle and can be helpful in its control. For example, it can be used for visual odometry and slippery correction. The pressure sensors, inclinometers and gyroscope mounted on the body give the posture (position and orientation) of the body in its environment. On the other hand, the laser range finder work like a light house, projecting a laser beam to measure the distance between the body and the impact point. The LRF is rotating on an axis to scan a plan from nearly 180 degrees, and an additional servo is rotating on 360 degrees the LRF on a perpendicular axis to allow the scan of its entire environment. The detection of the environment is done around 5 meters around the robot and gives results as shown in the picture below.

Figure 5: Image of two hexapods in a crater obtained with a laser range finder.
2.1.2 Controls & Communications
All controls and communications are achieved passing through the onboard computer located in the middle of the platform. This computer is a Vaio UX 91 ensuring adequate performance of the system. The Vaio can communicate with one or many external users via Bluetooth, wireless network, keyboard or touch screen.

On the other hand, the Viao communicates with feedback sensors and actuators via serial and USB ports as well as a Bluetooth connection. Although it is not recommended all limbs are connected together in a star configuration and each limb communicate in a daisy chain. The communication is using a RS485 standard which is converted in USB for the computer. The webcam, LRF and inclinometers are readily compatible with computer based system. However, the pressure sensors are sending analog data that require processing in order to communicate properly with the Viao. A microprocessor SH2 (SH7046) from Renesas is used to convert the signal and send it through RS232 serial communication. The SH2 and the software code were already developed for three sensors but needed modification to allow for a fourth sensor. The modified code is included in Annex A. As per the remaining two sensors they are located on the wheels which are discussed thoroughly in section 2.3.

2.1.3 Power, Motion & Support
The body is a regular hexagon of 120mm on each sides and made of aluminum to reduce the overall weight of the platform. Its size was determined in order to accommodate the limbs, the computer and all electronics. Each one of the six limbs possesses 4 degrees of freedom and is actuated by Dynamixel smart servos with Maxon motors, including 1 AX-12 and 3 DX-117 providing a total of 24 degrees of freedom to control the robot in its environment. Although, the Viao has its own battery, all actuators are powered by lithium polymer battery of 14.8 V supplied by Hyperion and can provide 2500mAh per battery. A total of 4 batteries are used to ensure long lasting performances. The characteristics of Dynamixel are listed in the table below.
Table 1: Main specifications of DX-117 & AX-12. [Dynamixel, 2006&2005]

<table>
<thead>
<tr>
<th></th>
<th>DX-117</th>
<th>AX-12</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (g)</td>
<td>66</td>
<td>55</td>
</tr>
<tr>
<td>Gear Reduction Ratio</td>
<td>192.6</td>
<td>1/254</td>
</tr>
<tr>
<td>Input Voltage (V)</td>
<td>12</td>
<td>16</td>
</tr>
<tr>
<td>Final Max Holding Torque (kgf.cm)</td>
<td>28.89</td>
<td>38.52</td>
</tr>
<tr>
<td>Sec/60degree</td>
<td>0.172</td>
<td>0.129</td>
</tr>
<tr>
<td>Resolution</td>
<td>0.35°</td>
<td>0.35°</td>
</tr>
<tr>
<td>Operating Angle</td>
<td>300°</td>
<td>300°, Endless Turn</td>
</tr>
<tr>
<td>Voltage</td>
<td>12V−16V (Recommended voltage: 14.4V)</td>
<td>7V−10V (Recommended voltage: 9.6V)</td>
</tr>
<tr>
<td>Max. Current</td>
<td>1200mA</td>
<td>900mA</td>
</tr>
<tr>
<td>Operating Temp.</td>
<td>-5°C ~ +85°C</td>
<td>-5°C ~ +85°C</td>
</tr>
<tr>
<td>Command Signal</td>
<td>Digital Packet</td>
<td>Digital Packet</td>
</tr>
<tr>
<td>Protocol Type</td>
<td>Half duplex Asynchronous Serial Communication (8bit,1stop,No Parity)</td>
<td>Half duplex Asynchronous Serial Communication (8bit,1stop,No Parity)</td>
</tr>
<tr>
<td>Link (Physical)</td>
<td>485 Multi Drop (daisy chain type Connector)</td>
<td>TTL Level Multi Drop (daisy chain type Connector)</td>
</tr>
<tr>
<td>ID</td>
<td>254 ID (0~253)</td>
<td>254 ID (0~253)</td>
</tr>
<tr>
<td>Communication Speed</td>
<td>7343bps ~ 1 Mbps</td>
<td>7343bps ~ 1 Mbps</td>
</tr>
<tr>
<td>Feedback</td>
<td>Position, Temperature, Load, Input Voltage, etc</td>
<td>Position, Temperature, Load, Input Voltage, etc.</td>
</tr>
<tr>
<td>Material</td>
<td>Full Metal Gear, Engineering Plastic Body</td>
<td>Engineering Plastic</td>
</tr>
<tr>
<td>Motor</td>
<td>Swiss MAXON Motor</td>
<td></td>
</tr>
</tbody>
</table>

Since 18 DX-117 are used and 6 AX-12 a total of 24A can theoretically be required to actuate the robot in the worst case scenario. The power consumption of the microprocessors, sensors and other electronics can be estimated to be less than 1A. Thus giving a total of less than 25A in order to properly operate the robot. This worst case scenario although totally unlikely would still be able to operate for 24 minutes. Preliminary tests indicate that a power consumption of 5A for walking would be a more realistic value. This would allow for longer test durations or even removal of a battery and thus mass.
2.2 Limbs

The limbs are the skeleton of the robot. They are responsible for the walking and divers manipulation tasks.

![Limb configuration.](image)

Each limb is composed of four simple parts. The hand located at the end can be modified to perform multiple tasks as well as walking. The arm provides the length required for walking over rocks in unfriendly terrain as well as its rigidity. The elbow is used mainly during the walking scheme and for rolling but it can also provide more flexibility during manipulation. It is the only region composed of two degrees of freedom.

2.3 Wheel

As the wheel is a specific configuration of the limb, the connection between the body where the processing unit and power source are, and wheel where the actuators and sensors are located is an issue. This sub section discusses the different technical solutions addressing the problem of transmitting power and establishing communication between each side of the rotating parts of the robot.
2.3.1 A wireless limb

As the connectic becomes an issue, a way to solve the problem is to avoid it by using a wireless solution. If each hybrid limb owns its own power source and is able to transmit data from its sensors and receive goals for the smart actuators to the processing unit on the body, then the hybrid limbs becomes independent of the rest of the robot and the issue is solved.

In order assure the wireless connection a SH2 board is used with a Bluetooth module plugged on one of its serial port. The board and the actuators are alimented by a separate battery at the end of the limb. Sensors like the pressure sensor at the end tip are connected to the analog port of the board. The hybrid limb is simply attached on the horn of the endless turn actuator (Dynamixel AX-12) that provides the driving power of the wheel.

Cons

- A dedicated microcontroller is required to manage communication between the hybrid limb and the body. As the Dynamixel DX-117 actuators used in limb mode are accessible through a RS485 serial connection, special development efforts in software and hardware are required to implement the communication on the microcontroller board.

- The wheel needs a battery that adds some extra-weight, and becomes an issue of repartition of mass in the wheel. The inertia matrix of the wheel becomes asymmetric and special care need to be taken for the balance control of the body in wheel mode.

- In case of disconnection in leg mode, the stability of the robot is compromised as the limb will not respond to any actuation. Hence, some extra software efforts need to be taken in the main controller of the robot to verify constantly the status of the connection.

- For some reasons, the serial to Bluetooth module transmitting real time data for the actuators is buffering information and sending them with delay. Some ad-hock software solution based on padding until the Bluetooth module flushes can be implemented but are not very elegant nor efficient.

- The simple attachment of the hybrid limb on the plastic body of the Dynamixel AX-12 smart actuator as seen in figure 6 is a weak point of the
Pros

- Independent limbs can be developed and tested separately
- The attachment of the hybrid limb on the body becomes trivial as no complex mechanical interfaces are required.
- This is a high tech and cool solution

2.3.2 Using a slip ring

A common technical solution to assure a wired connection between two rotating parts is to use a slip ring. It is a mechanical interface where several wires can be linked to each others on the two sides of the rotating parts.

Cons

- The analog signal provided by the pressure sensor needs to be digitalised because of the electrical noise in the slip ring. It is never accurate to have the power channel and the communication channel too close to each other, especially when the power transmitted is very high (each of the three servos can consume up to 1.2 A, hence the total power to transmit can be more than 3.6 A). The solution requires having a micro controller board on the hybrid limb to accomplish this digitalisation's task.
- The price of a slip ring is very high, and it drastically increases with the number of channels and power to transmit. In our case, we need to transmit a high power of at least 3.6 A (two channels), a RS485 serial signal for the actuators (two channels), and a pressure sensor signal (three axis hence three channels). It is possible to digitalise the analog signal of the pressure sensor and use the same channels as the RS485's one, saving two channels. But using the same media for the actuation and the digitalized pressure sensor data is not advisable as the actuation performances might be reduced as the bandwidth is necessary reduced.
Usual slip rings are necessarily located on the rotating hollow shaft that owns the wires. One side of it is attached to the shaft and the other side is fixed to the non rotating part. Hence, except for very expensive and cumbersome through-bore s one, the slip ring is required to be located at one end of the shaft, exactly like a motor. Usually, at one end of the shaft is the motor and at the other is the slip ring like in the left part of the 7. When the shaft is held only on one side, it is necessary that the slip ring is located at the beginning of the shaft. The motor needs to have the shaft going through it as seen in the right part of figure 7 or need to be deported on the side, and transmit the power trough a gear or a belt.

- The mechanical attachment of the hybrid limb on the body is heavier and more complex to implement.

![Figure 7: Slip ring’s assembly.](image)

Pros

- There is no need to constantly check by software the connection between the robot and its hybrid limbs as the connection is not wireless. The solution is more reliable.

- There is no need to add extra battery on the hybrid limb if the slip ring transmits the power from the batteries in the body.

- If the actuator of the wheel is not located on the wheel s shaft, using a belt to transmit the driving torque, the system is more complex but more reliable (a too high torque will not break the mechanical interface like in the previous wireless solution).
2.3.3 A hybrid technical solution based on wireless and slip ring

In the two previous technical solutions, to assure communication between the body and the hybrid limbs, several cons are strongly damageable for the system. In the slip ring solution, the most important one is the too high cost of implementation due to the specifications of the 4 channels slip ring. For the wireless one the most serious cons are related to the poor performances of the Bluetooth communication and the implementation of the RS485 protocol in the SH2 board that were discovered while prototyping this solution. The idea is then to find an alternative solution based on the two solutions.

To avoid the cost of two expensive slip rings transmitting high electrical power, it was decided to use the solution of the wireless hybrid limb concerning the extra battery on the wheel. The advantage of this solution is that the slip ring is limited to two channels transmitting only data for the Dynamixel protocol (on the RS485 serial communication). In this case, as the rotation speed of the wheel is not very high, a simple male-female jack connector can be used as a costless two channels slip ring. The SH2 board on the wheel will then not have to deal with the implementation of the rs485 protocol and the Bluetooth module can be used to transmit less real time data from the pressure sensor using padding of information to flush the buffer.

![Figure 8: Slip ring assembly.](image-url)
The implementation of the actuator for the transmission of the driving power is still complex as using a belt, but safer for the mechanical hardware and allows an easy changing of the driving actuator.

This solution is still under development and was not implemented nor tested during the next phase. The next phase discussed in the following chapter regards the fabrication of the platform.
"My mind tells me to give up, but my heart won't let me.” Unknown

The fabrication of the robot has been tedious mainly because of budgetary reason. The limited budget allocated for the fabrication of the hardware has forced us to manufacture all parts from aluminum plates and bars using only a press drill, a band saw and manual tools. Many days and nights were spent on the fabrication of the parts. Narrow tolerances were hard to achieve and many parts needed to be machined or adjusted more than once. Using all the material available and armed with patience a prototype platform has been successfully built. Using a progressive approach of implementing of one feature at the time allowed making constant progress at a fast pace.

This section will focus on the development of LEON. The fabrication steps that were used will first be discussed accompanied by problems that were face and solutions that were taken. The fabrication process will be followed by the calibration of the hardware and the development of the gait that allowed the robot to walk properly on a flat surface. It will be followed by a brief summary of the next steps to come in the development of the platform.

### 3.1 Fabrication steps

After getting familiar with the concept, the CAD software and the laboratory tools, initial machining of the limbs and the base platform was executed. Even without current the servos were showing enough resistance to maintain the robot in a standing position. The picture on the right hand side is showing the beginning of this novel
platform. Once the limbs were well advanced, the focus turned on the wheel. This wheel represents the main challenge in the fabrication of this platform. Although the connection problem was discussed in the previous section and the diverse components integrated in the wheel were well defined. The actual mechanical design was far from being completed. Since the wheel is also a limb it has to have special characteristics such as: the same length as the other limbs, the same number of degrees of freedom, the lowest mass as possible, no interference with the body, flexibility and minimal gaps on the surface of the wheel. Many concepts were discussed before choosing the best folded wheel approach. And a mechanical hinge design was selected because of its simplicity and its reliability. As depicted in the preliminary prototype below, the wheel has to have sufficient clearance to prevent contact with the body. The hinge approach is also showing flexibility. Moreover, a spring loaded hinge ensures that the wheel part open in the right direction preventing failure of the concept.

Figure 10: Initial wheel design.
In order to have the proper flexibility, the hinge mechanism must have the proper length and position. Also, it has to be located as close as possible to the side of the wheel to prevent excessive gap during wheel mode. The figure 11 shows the first completed wheel without battery. It proved that the concept can work.
However, many components are missing in this first prototype. The main one being the battery. Furthermore, the batteries are the second heaviest components of the system only surpassed by the main computer of the robot and they represent all together more than 15% of the total mass of the robot. Beside its mass, its actual size is cumbersome and difficult to integrate within the wheel especially with the hinge solution. That is why judiciously locating the battery on the wheel is crucial and represents a great challenge.

It was finally decided to locate it in the hand section of the limb where its mass would be less emcumbering the servos. It is also where it would be close to the center of the wheel as well as where space is sufficient for its size. Having a center of inertia as close as possible to the center of the wheel is crucial for the wheel performances and prevent the need of requiring additional counterbalancing mass. The protective box covering the battery was made in plastic to minimize the mass.

However, preliminary test on the wheel showed that the plastic conection between the AX-12 and the wheel limb was suffering from large deflexion and that its balance
was far for perfect. These problems are pointing towards a slip ring solution that would allow reinforcing the connection and gearing the system to increase its torque. Furthermore, the required size for the protective box on top of the battery has forced us to enlarge the wheel radius by 1 cm thus considerably augmenting the gaps on the wheel surface. This was necessary to maintain degrees of freedom in the limb mode. The following three pictures demonstrate the problems that were mentioned and encountered during the fabrication.

Figure 12: Battery protection and installation on the wheel.
Figure 13: Flexibility diminished when using the bracket developed for the first prototype.

Figure 14: Gaps encountered in the wheel.

Although these problems are time consuming to debug and require to remachine all the parts to relocate the hinge towards the end of the side of the wheel. None of them cannot be overcome.
Since the robot was required for a TV demo and there is only a limited number of servos. All efforts were removed from the wheel design to concentrate on the finalization of a limbs robot. The wheel was even dismantle in order to prevent the press from having access to this novel idea before a publication is presented. Nevertheless, new parts fabricated were made with the wheel configuration in mind so that it will be easily modifiable to a wheels/limbs robot later on. The picture below shows the robot in a frog like design.

Figure 15: Working towards a TV demo.

A webcam was used instead of the wireless camera and the software was developed to carry on the walking endeavor. As shown below, a setup was made for the demonstration and many tests were effectuated in order to prevent major problems from occurring. But even if the hardware was completed, many more tasks were still required to enable a robot to walk properly.

Figure 16: LEON TV demonstration setup.
3.2 Calibration

One of the first tasks performed was the calibration. The servos used for this robot are actuated by position and in order to have a uniform robot all limbs must be adjusted in reference to a model. In theory, the servos should return the angle depicted in the figure below in standing position. The servo at the elbow should be straight when it returns a 0° value, the servo at the arm should give a 90° value and the last one should return a 0° value. However, because of manufacturing and assembling tolerances the servos do not return such values and software calibration of each actuator must be performed. Note that the servos were assembled to allow motion from -150° to 150°.

![Figure 17: Theoretical position of servos](image)

The results of the calibration are listed in the table below. The values show that variations ranging from 0-23 degrees can be obtained.
<table>
<thead>
<tr>
<th>Limb #</th>
<th>Servo #1 (degree)</th>
<th>Servo #2 (degree)</th>
<th>Servo #3 (degree)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>-7.5</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>-6</td>
<td>-1</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>-5</td>
<td>1</td>
<td>23</td>
</tr>
<tr>
<td>3</td>
<td>-5</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>4</td>
<td>-8</td>
<td>-2</td>
<td>19.5</td>
</tr>
<tr>
<td>5</td>
<td>-5</td>
<td>3</td>
<td>21</td>
</tr>
</tbody>
</table>

### 3.3 Gait

Once the robot is calibrated, walking scenarios must be programmed. The term “gait” is used to describe the phasing problem experienced by leg motion. This problem comes from the fact that a leg is a discontinuous element unlike a wheel. Therefore it must be lifted at the end of its effective stroke, returned, and placed to begin another support stroke. As for other walking vehicle, a gait of a hexapod can be defined as the time and the location of the placing and lifting of each foot, coordinated with the motion of the body in its six degrees of freedom in order to move the body from one position to another. By consequence, gaits describe and determine the speed, the direction of motion and the mobility of a walking machine. As shown in nature, different gaits can be used according to different situation in order to have more stability, fluidity or speed. For example, horses can choose walk, trot or gallop depending on the situation and the environment.[Song & Waldron, 1989] The hexapod possesses three different gaits namely: the tripod gait, the wave gait and the ripple gait. They represent the all stable cases where 3, 4 or 5 limbs are in contact with the ground.[Ferrell, 1994]

The tripod gait, as its name suggests, represent the case where three limbs are always in contact with the ground. It consists of the front and back limbs on one side and the middle limb on the opposite side. For each tripod, the legs are lifted, lowered, and moved forwards and backwards at the same time. A hexapod consecutively uses its 2 tripods shifting the weight alternatively from one to the other. Since 3 limbs are on the ground at all times, this gait is both "statically" and "dynamically" stable.
As per the wave gait, all limbs on one side are moved forward one after the other, starting with the rear-most limb. The same motion is then repeated on the other side. Having 5 limbs on the ground at every moment and only 1 limb is lifted, provides high-stability posture for the robot. But this stability comes with a cost. The problem faced with the wave gait is that it cannot be speeded up too much. If the suspension phases is shorten then the steps will get shorter and/or the limbs will have to require more energy. Moreover, overlapping the suspension phases would lead to lifting adjacent legs at the same time which in turn entails to partial collapse of that part of the body.

The last possibility is the ripple gait. The timing of this gait is performed using a local wave on each side comprising non-overlapping lift phases with the other side. That means that the 2 opposite side waves are 180 degrees out of phase with one another.

Figure 18: Graphic illustrating the 3 motion schemes of a hexapod. [Ferrell, 1994]

The motion scheme can be easily visualized by carefully looking at the figure above. On the graph, the numbers adjacent to the legs in the body diagram correspond to time points. The tripod gait, on the left side, is the fastest if step size remains constant. It can complete a cycle in 2 time beats while the wave gait requires 6 beats.
Because of its overlapping particularity, the ripple gait completes a cycle in 3 time beats even though the phasing-offset actually produces 6 mini-beats overall.

The stability of the robot is closely linked to the number of limbs in contact with a surface. Thus, the wave motion will be most stable, since it keeps the most legs on the ground at all phases of the stride. It is also the motion that is likely to be the most adequate for highly uneven terrain. The ripple gait is next most-stable. At every time, only 2 legs are ever off the ground. Only 1 leg per side is ever lifted at a time, and when it is, its direct opposite counterpart is down. Furthermore, because of the phase offsets between sides, no 2 legs are ever in full suspension at any time. The tripod, although fastest, will also be the least stable, since it always has 3 legs in suspension.

The tripod gait was selected and implemented for testing the hardware on a flat surface with natural rocks. This configuration allows characterization of its speed, robustness and stability. The gait file was validated experimentally and is included in Annex B.

![Figure 19: Breakdown of the tripod gait.](image)

In the figure above, a breakdown of the tripod gait cycle is shown. Images shown on top are part of the first beat and the ones at the bottom represent the second beat of the cycle. The complete cycle takes about 2 seconds and allows making constant steps of 6cm and a total of 12 cm per gait giving an approximated speed of 6cm/sec. The hexapod configuration allows for quasi omnidirectional motion and its stability
is maintained during the entire gait. As shown in the figure 20, the center of gravity remains well within the boundary of the tripod ensuring at the same time its stability.

![Figure 20: Gait stability area.](image)

However preliminary tests on the hardware demonstrated that the brackets used for the arms were considerably lacking rigidity. Excessive plastic deformations were experienced leading to major modifications of the part. The location of this unacceptable deformation is shown in the picture below.

![Critical bending area](image)

![Figure 21: Critical bending in the arm.](image)

A “T” bar was then adopted to improve the rigidity of the structure in respond to bending moment while maintaining a mass as low as possible.
### 3.4 Max obstacle that can be overcome

One of the main reasons to have a robot with limbs is to overcome obstacles or uneven terrains that cannot be done using wheeled vehicles. The actual tripod gait allows to go above object that are about 75 mm high.

Although, the actual hardware is mechanically limited, a simple modification of the bracket would allow gaining extra height and prevent contact of the parts. However, special care should be taken so that the wheel configuration remains possible to achieve.

### 3.5 Next steps
Unfortunately three months is too short to allow developing, building and debugging a whole wheels/limbs platform. It will not be surprising to learn that further steps need to be accomplished in order to complete this innovative platform. Here is a non exhaustive list of the work to come on this project.

Although the platform is now able to walk, it is totally ignorant of its environment. The implementation of feedback sensors is therefore essential. The pressure sensor located at the end of each limbs will provide information about contact with the ground and also allow the platform to walk on uneven surface using each limb more efficiently. Inclinometers are also essential for the wheel control as well as to determine the posture of the vehicle in remote application. The webcam and the laser range finder are both important tools for closing the control loop.

The implementation of the wheel is also required in order to complete this innovative platform to fully perform its intended goal. Once the hardware will be completed its characterization will be essential to be able to pursue research with it.
Chapter 4  
Platform Potential Research

“It’s human nature to stretch, to go, to see, to understand. Exploration is not a choice, really; it’s an imperative.” - Michael Collins, Gemini and Apollo astronaut.

This report would not be complete if it would not encompass the motivation behind the development of this platform. That is why the present chapter will discuss present and proposed research that could be done using this limbs/wheels robot. The advantage of having a hybrid design is that it allows to simulate the teleoperation platform in diverse environments close to the real application.

4.1 Present research related to research plan

Development of a Networked Robotic Teleoperation Platform Applied to Disaster Mitigation using Mixed Reality

After the Hanshin-Awaji earthquake in Japan in 1995, the development of robotic systems for search and rescue operations received increased attentions and national priority. A quick evaluation of the extent and degree of damages is necessary in case of such a disaster, in order to start efficient recovery programs to minimize the loss of human life and facilitate rapid restoration. But greater the disaster is more difficult it becomes to start rescuing and surveillance, as the access of human teams becomes tough and communications networks unavailable. The development of a teleoperation platform for mobile robots for surveillance and rescuing missions becomes handful to mitigate the disaster by saving lives and avoid an additional loss of human rescuers. Since 2003 the Japanese Ministry of Internal Affairs and Communications is supporting the development of a robotic system capable of collecting vital information for the understanding of the structural conditions of the examined area and the rescue of surviving victims.
This current system is formed by three mobile robots: two twin crawlers that have search-and-recognition tasks gathering information about their surroundings, and an outdoor wheeled rover that approaches the area carrying the two crawlers to deploy them at a specific spot such as the inside of a building. To teleoperate the three robots, the integration of a satellite-based IP communication, linked to the Japanese satellite ETS-VIII is scheduled. In this case the teleoperation platform will have to handle short delays in the communication and lower bandwidth. Then, in order to be able to navigate the robots remotely, a camera feedback is not adapted as the video stream is bandwidth consuming and any delay or light conditions becomes dangerous. Laser Range Finders (LRF) are mounted on the robots, to save bandwidth and provide the operator a better understanding of the environment, displaying a 3D view of the scene.

The developed teleoperation platform allows a manual control of multiple robots through a Mixed Reality feedback. The use of both video and a 3D reconstructed environment model allows the operator to navigate in the disaster scene. The video feedback provides a view of dynamical changes of the environment but is not primordial to the navigation. A drawback of a current platform, however, is that the direct navigation through it becomes impossible as the delay in the media increases, preventing its use in case of space missions where the range of time delay between earth and the mission is minutes or hours.

4.2 Purpose of proposed research

The first purpose of the proposed research is to develop a new effective teleoperated platform that will deal with long time delays for space robotic mission by investigating:

_ a novel architecture for the platform that offers an offline supervisory control,
_ Simultaneous Localization And Mapping (SLAM) algorithms to provide a refined posture and mapping data coming from the proprioceptive and exteroceptives’s sensors of the in-situs environment of the robot on the mission.
The second purpose of the research is to deal with different gravity and contact issues using a Hybrid Simulation where virtual model for dynamic simulation will be coupled to a test field, where a physical model (mock-up) similar to the actual robot on the mission is evolving in a manually reconstructed environment similar to the one on the mission (c.f. Spirit and Opportunity mission’s Mars yard). As gravity on the mission’s site might different than earth’s one, we will investigate solutions to simulate gravity on the mock-up, by attaching it on a robotic manipulator equipped by a force/torque sensor. Virtual models are difficult to use to simulate accurately contacts on uneven soil surface but they accurately provide a global view of the environment of the robot necessary for a supervisory control as proved in the current research. On the other hand, physical models are providing accurate evaluations of the behavior of the robot at each moment on the mission, but cannot provide a general overview of the environment. We will investigate Hybrid Simulation combining both virtual model and physical one.

4.3 Proposed plan

An Integrated Teleoperation System for Robotic Exploration Missions Based on Hybrid Simulation

As robotic lunar exploration will be a central focus of NASA and JAXA missions for the coming several years, there is a need of effective teleoperation platform that deals with time delay and different gravity. In lunar applications, gravity is an issue, so Prof. Yoshida is working on the modeling and simulation of traction mechanics of vehicles under different soil characteristics and gravities. This research will be integrated the proposed platform for accurate motion control on the mission. For the implementation of the Integrated teleoperation system, the proposed modular platform depicted in figure 24 has four core modules.
The Mission Module is the teleoperated robot on the mission. The basic requirement for the robot is to achieve scientific investigation and mapping of the surface at multiple locations with fine positioning capability once landed. For this purpose, a wheeled or legged mobile robot is equipped by several types of sensors attached to its controller on board, like a LRF fixed to the body to scan the environment of the robot. Data from inclinometers and odometry will be used for orientation and localization purposes. The prototype will be used, at first, as a test bed to simulate either the real mission scenario, or to elaborate motion strategies and the full teleoperation platform. It will implement the same behaviors as the robot on the mission and will be used later in the test field during the path selection process. The robot on the mission is a state machine that is waiting and executing scenarios provided by the ground control module and sending to it sensory data.

The Ground Control Module is the link between the Earth and the mission. The communication interface is able to manage the connection with the mission, uploading the files containing the sequences of commands for the next motion and downloading files that contain the sensory data: internal sensors to compute the pose.
of the main body, external sensors to define the environment and the scientific instruments’ data. The sensory data representing the latest status of the mission is forwarded to the Simulation Module.

The Simulation Module’s purpose is to simulate and generate the possible scenarios for the mission. The latest update of the sensors of the robot is providing the sensory data of the LRF and odometry information to the Elevation Map Builder sub-module. This one will be using S.L.A.M. and referencing algorithms to define a more precise pose of the body of the robot for the virtual model in its virtual environment and build a refined map of the location. Either a real-time dynamic engine using a virtual model of the robot in the sensed environment or a hybrid simulator will be used to generate the set of commands. The real-time dynamic engine allows the operator to control the motion of the virtual robot with a joystick. The succession of commands that generates the motion is logged and defining a mission scenario. The hybrid simulator is a robotic system that holds a mock-up of the robot to simulate the gravity on the mission in a rebuild environment on the test field. The effects of mission’s gravity on main body pose of the mock-up is computed by a dynamic engine and actuated by the robotic system. Reaction forces of the test field on the mock-up are detected by the force/torque sensor and used to compute the resultant motion of the main body. Investigation on how to combine the results of this simulation with the one of the virtual robot in contact with its virtual environment will be done in order to get more accurate simulation’s results. One should notice that in the development stage prior to the mission, the simulation environment is used as a test-bed to elaborate and test motion strategies of the controllers in an emulated gravity.

The generated scenarios are discussed, replay and eventually edited (to add passive commands) in the Decision Module. The most appropriate one is selected to become the next move of the mission and is transferred to the ground control module to be uploaded to the mission.
4.4 Expected results and impacts

The proposed platform would provide a necessary and useful tool in the development of advanced technology and its verification for the remote operation of lunar and mars exploration rovers. In addition, the proposed platform is expected to be used for two type of extensive applications. The first one is the missions for disaster mitigation, mentioned in the current activity. After the proposed research, the teleoperation platform with larger time delays and the SLAM. based environment builder technology for more difficult environments would be strengthened. The authors will be able to apply this technology for the investigation of active volcanoes, where the surface is more rough and rocky and where the robots should be remotely operated far from the civilization. The second type of application is an extreme case of remote explorations such as a recent Japan's Hayabusa asteroid mission, where the teleoperated platform has to manage very large time delay and micro gravity. One should notice that in these conditions, legged robots become a more appropriate technological choice than wheeled ones for fine positioning capabilities, and the proposed platform becomes an appropriate test-bed for walking strategies in such conditions. Those applications have a strong impact to promote our scientific knowledge on earth and other planets and increase the safety of our lives on earth.
Chapter 5

Conclusions

“There was a universe, a poem, frozen on the boundaries of human experience.” -- William Gibson

There are no optimal solutions that encompass all situations. Although wheeled vehicles have been improved and proven to be very efficient to operate on paved surfaces operating on uneven terrains still remains challenging. In the context of space exploration it is even more important in order to extract the full science potential of a planetary body at the minimum cost. A hybrid solution with wheels and limbs represents an ideal platform that offers efficiency, mobility and speed on all terrain. At first the background of the concept was described. Then, the development and fabrication of such platform was discussed. And finally the platform potential for research is demonstrated.

LEON is still in its infancy but has enormous potential. There are still a lot of work to be accomplished in order to verify and exploit the concept but it still remains a novel design of a hybrid limbs/wheels robot that can be applied to simulate different case study. For example, simulating the exploration of the Moon’s South Pole or even the Hayabusa mark 2 when used with a manipulator to simulate microgravity. The platform can also be used with telerobotic for application of disaster mitigation or volcano’s exploration. The applications researched have strong impact to promote our scientific knowledge on earth and other planets and increase the safety of our lives on earth.


Rohmer, E. et al., 2006a. A Novel Distributed Telerobotic System for Construction Machines Based on Modules Synchronization, IROS 2006 Pekin China.

Rohmer, E. et al., 2006b. A High Level Teleoperation Platform for Space Robotic Missions. Tohoku University. Space Robotic Laboratory. SMC-IT, JPL NASA, US.

Appendix A

Analog Sensor Recording

Fichier main.c

//
// Programmed by Daisuke Endo
// Modified by Alexandre Frechette
//                    2007/08/04
//

/*****************************************************************
****
***** ポーリングによる AD 変換入力
*****
***** 割り込みベクタの設定
***** ベクタ番号 関数名 言語
***** なし
*****
***** 入力端子
***** チャンネル 端子名 弊社 CPU ボードコネクタ
***** 8    AN8  CN2-28
***** 9    AN9  CN2-29
***** 10   AN10 CN2-30
***** 11   AN11 CN2-31
***** 12   AN12 CN3-1
***** 13   AN13 CN3-2
***** 14   AN14 CN3-3
***** 15   AN15 CN3-4
***** 16   AN16 CN2-32
***** 17   AN17 CN2-33
***** 18   AN18 CN2-34
***** 19   AN19 CN2-35
*****************************************************************/

#include <stdio.h>
#include <sysio.h>
#include <stdlib.h>
#include "YSML.h"
#define AVE_COUNT 100

short offset[12];
short data[12];

void wait(unsigned long count)
{
    unsigned long x;
    for (x=0; x<count; x++) ;
}

void init_AD(void)
```c
{  
  int ch, i;  
  long temp[12] = {0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0};  
  for (ch=0; ch<12; ch++) PAdInit(8+ch);  
  wait(10000000);  
  for (i=0; i<AVE_COUNT; i++) {  
    for (ch=0; ch<12; ch++) {  
      temp[ch] += (long)(PAdIn(8+ch) & 0x0fff);  
      wait(1000000);  
    }  
    for (ch=0; ch<12; ch++) {  
      offset[ch] = (short)(temp[ch] / AVE_COUNT);  
    }  
  }  
  }  

void get_AD_data_AVE(void)  
{  
  int i, ch;  
  long temp[12] = {0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0};  
  for (i=0; i<30; i++) {  
    for (ch=0; ch<12; ch++) {  
      temp[ch] += (long)((short)(PAdIn(8+ch) & 0x0fff)-offset[ch]);  
      wait(100000);  
    }  
    for (ch=0; ch<12; ch++) {  
      data[ch] = (short)(temp[ch] / 30);  
    }  
  }  
  }  

int main(void)  
{  
  int ch;  
  init_AD();  
  while(1) {  
    get_AD_data_AVE();  
    for (ch=0; ch<12; ch++) printf("%d ", data[ch]);  
    printf("\n");  
    wait(1000000);  
  }  
  return 0;  
}
Appendix B

Tripod Gait Summary

Fichier tripod.txt

# gait 1 cycle 1 phase even up
0 0. 90. 0.
2 0. 90. 0.
4 0. 90. 0.

# gait 1 cycle 3211317 phase move uneven's hips
1 20.2 60.58 -22.74
3 -0. 48.7 -75.35
5 -20.2 60.58 -22.74

# gait 1 cycle 1 phase even down
0 0. 60. -30.
2 0. 60. -30.
4 0. 60. -30.

# gait 1 cycle 1 phase uneven up
1 0. 90. 0.
3 0. 90. 0.
5 0. 90. 0.

# gait 1 cycle 1 phase move even's hips
0 0. 55. -12.1
2 20.2 60.58 -22.74
4 -20.2 60.58 -22.74

# gait 1 cycle 1 phase uneven down further
1 0 60 -30
3 0 60 -30
5 0 60 -30