LIMBED EXCURSION MECHANICAL UTILITY ROVER: LEMUR II

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Abstract

The assembly, inspection, and maintenance requirements of permanent installations in space demand robotic agents that provide a high level of operational flexibility relative to the mass and volume of the robotic system. Such demands point to robotic platforms that are dexterous, have significant processing and sensing capabilities, and can be easily reconfigured (both physically and algorithmically). Evolving from the LEMUR I platform, the LEMUR II design is intended as a extremely capable system that both explores mechanical design elements and provides an infrastructure for the development of software architectures (particularly cooperative multi-agent) and algorithms (such as adaptive visual feedback). The layout of the system consists of six, 4 degree-of-freedom limbs arranged axi-symmetrically about a hexagonal body platform. These limbs incorporate a "quick-connect" end-effector feature below the distal joint that allows the rapid change-out of any of the four current tools available: a simple foot/pointer end, camera, task light, and a rotary driver with a bit collet and integrated reaction torque sensor. Each quick-connect also includes a load washer for feedback of force axial to the end-effector. The other major subsystem is a stereo camera set that travels along a ring track, allowing omnidirectional vision.

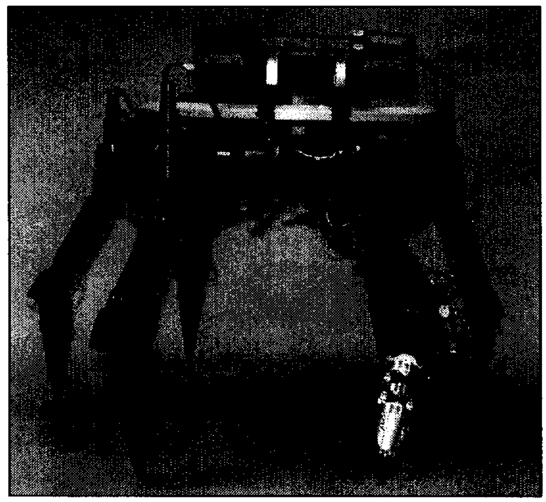

Figure 1. The LEMUR II platform during assembly

Orbital Construction Robot Design Problem

The extended reach and duration of humanity and humanity's instruments in space will require the in-space construction of facilities that are either too large or too distant to be entirely assembled and maintained by astronauts. Instead, some semi-autonomous robotic systems will have to be incorporated in the assembly, inspection, and maintenance of those facilities. These systems will only be enabled by new methods and technology that squeeze the greatest capability and flexibility from the hardware flown. Moreover, these facilities will require a greater number of robot agents working in concert than has been previously implemented. Essentially, reaction to unplanned or unstructured problems with a heterogeneous, multi-agent team with the inclusion of humans in the loop represent *sine qua non* requirements of humankind's expansion into space. In fact, the basic problems now presented by space construction are general enough that their solutions will have repercussions throughout the field of robotics, ranging from planetary exploration to factory automation.

In addition, some considerations must be made for the environment and structure of a station environment. There are, of course, provisions that must be made for operation in the cryonic-vacuum and high-radiation of a space setting. Some attention must also be paid to the impact of a robotic design on the station design and operation. Related to the question of hardpoints is the dynamic interaction between robot and station.

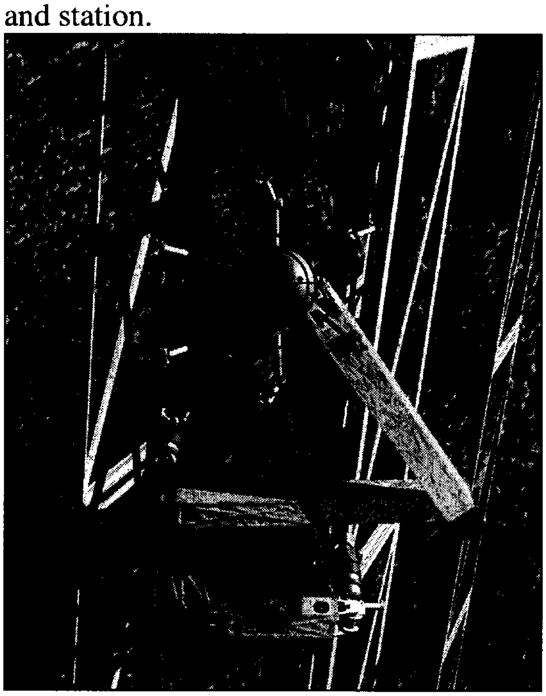

Figure 2. A future concept of LEMUR works in cooperation with Skyworker (CMU) on a space-based truss structure

LEMUR II Design Parameters

Because the design objectives of orbital robots are so ambitious, broad and rigorous, extensive prioritization had to be made. JPL decided to focus on a platform for the inspection and maintenance of small scale structures (~1m^3) because of the wide applicability of such a platform to space-based structures, large or small. Given that no robot designed by the current effort was intended to be tested in space, the space-specific requirements were given the lowest priority. To wit, any provisions for operation in a high radiation, cryonic-vacuum environment were left to a later effort. Conversely, the robot needed to be tested in a 1g environment with as little infrastructure as possible. Therefore, the operation scenario was constrained to 2 dimensions without any gravity compensation. LEMUR II would have to walk on a flat floor while supporting its own weight.

For the first year, the goal tasks were defined as navigation to target, visual inspection, and fastener torquing. The operations were chosen to emphasize flexibility in tasking and function, both in the overall system and its constituent sub-systems. In essence, LEMUR II should get as much done with the smallest set of hardware, yet be able to adapt itself to as broad a set of hardware as necessary to complete all tasks.

Implementation Overview

Taking some inspiration from nature, it was clear that the primate model of multi-use limbs with tool-using capability could provide a path to the platform complexity desired. However, stepping beyond nature, it was decided that six limbs would be of more use than four. Such a multiplicity of limbs would allow for a stable base of three or more limbs while leaving two or more limbs available for cooperative manipulation operations.

For simple walking, there really only needs to be 2 degrees of freedom (DOF) in the shoulder. However, a robot that dexterously manipulates objects with the aid of stereo vision needs more sophisticated articulation. These limbs were given an extra DOF (roll) at the shoulder for a total of 4 DOF each. This dexterity allows the end effectors to be moved into the direct view of the stereo camera pair as well as more flexibility within the workspace.

The philosophy of modularity and flexibility extends to the electronics and software as well. Both systems are packages leveraged without significant change from other robots (FIDO, SRR, Inflatable Rover) built by the Planetary Robotics Lab at JPL. As testament to those characteristics, the other robots are wheeled, not limbed, and use 3,4, and 6 wheels, respectively.

A special note should also be made of the extensive use of parts made with the Selective Laser Sintering (SLS) process. This rapid prototyping method yields near full-density polyamide parts with excellent strength and low mass. With 24-hour manufacturing turnaround times and inexpensive pricing, parts could be tested and modified repeatedly. Moreover, future adaptation of the designs becomes fast and inexpensive as well. Finally, the laser sintering process allows part designs that are otherwise unmachinable, which yields many advantages, including the fusion of parts to decrease part-count and assembly problems. SLS parts include the main link, the majority of the quick-release parts, and the many of the tool parts.

Table 1. LEMUR II system summary

Mass (kg)	9
Limbs	6
Degrees of Freedom	24
Actuator count (max)	31
Processor speed (MHz)	266

Limb Design

The overall layout of a LEMUR II limb is extremely simple. While several robots of the same general body plan as LEMUR II (iRobot's *Ariel*, for example) have operated using cable tendon drives with remote motors, every joint in LEMUR II is driven by a direct geartrain. Such an arrangement was chosen over a tendon drive for several reasons. Perhaps most important is the impact a cable system would have on the permissible range of motion in the limb. Because a cable system requires a mechanical element (the cable) to pass from the base of the limb to the furthest joint, a provision must be made to guide that element through each previous joint. Usually, and certainly in a system as small as LEMUR II, such provisions would have restricted the range of motion of the proximal joints. As it is, LEMUR II's joints are only restricted by electrical cable windup. Moreover, a minimum of 4 cables would have to be passed through the shoulder to activate the knee pitch and shoulder pitch, making for a complicated design problem. Finally, the direct drive arrangement allows for a self-contained joint design, which in turn lends greater modularity to the overall limb design. In fact, the degrees of freedom of a LEMUR II limb could be increased from 4 with the addition of more joints and links.

All joints are run by 13mm, 24V DC motors built by Maxon. Each is equipped with 16 count encoders with quadrature for control feedback. Maxon also supplied the gearheads that provide the first stage of the geartrain (see Table 2). A major contributing factor to the successful design of the LEMUR II joints is the use of a new, smaller harmonic drive that became available in the last year. Manufactured by Harmonic Drive Systems, these Size 8 drives yield an order of magnitude better torque and two orders of magnitude better positional accuracy than the planetary and bevel gear system in LEMUR I, all in roughly the same volume. Each joint has a Hall Effect switch and matching magnet for absolute positioning feedback.

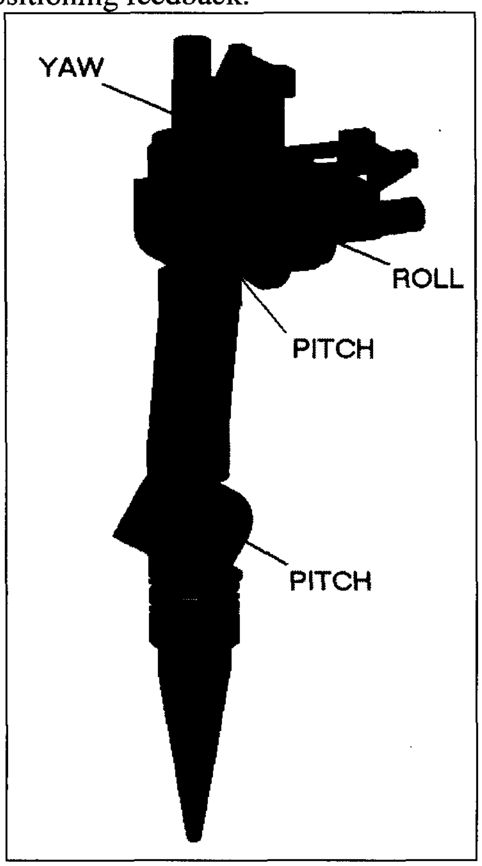

Figure 3. LEMUR II leg layout

Table 2. Joint actuation characteristics

1st-stage ratio (planetary)	16.58:1
2nd-stage ratio (harmonic)	100:1
max. torque (Nm)	9.0
max. continuous torque (Nm)	5.0
maximum speed (°/s)	45

The limbs are also quite simple in their kinematics. Key to this simplicity is the creation of a kinematically spherical shoulder. In addition to making the kinematic calculations straightforward, this arrangement results in a larger usable workspace because the volume of space precluded by singular configurations of the limb is reduced. In other words, the effector can be moved through more volume than the effector of a comparably sized limb with different kinematics

A heritage feature of the limbs from the LEMUR I design is the inclusion of a quick-connect. Similar to quick-connects for air-hoses, the locking action is performed by a set of balls that mate with pits in the stem of the tool. These balls are held in place by a spring-loaded collar. The mating surface normal to the tool axis is a custom load cell, which will be used to resolve reaction forces axial to the end effector.

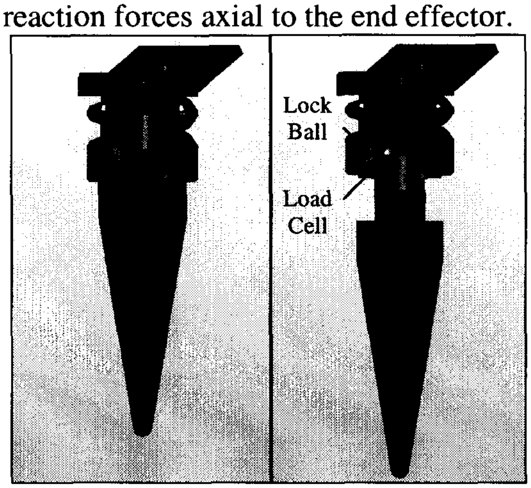

Figure 4. Quick-release in engaged and disengaged states

Tool Designs

Four basic tools are currently available for the LEMUR II platform: a simple end, a task light, a camera, and rotary driver.

Simple End

The simple tool is used as the basic end effector and has no other function than force transmission. The hemispherical tip acts as a virtual ball-joint.

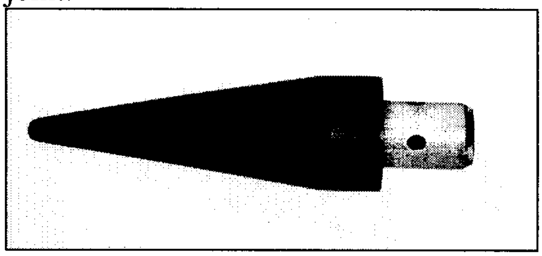

Figure 5. The simple end-effector

Task Light

The ultrabright LED light is used cooperatively with vision systems, both on LEMUR II and other platforms, to illuminate targets. The task light and palm-cam (see next section) are both based on a collet system that can be made to hold any cylindrical instrument or tool. Thus, the tools themselves are reconfigurable, further increasing the flexibility of the overall system.

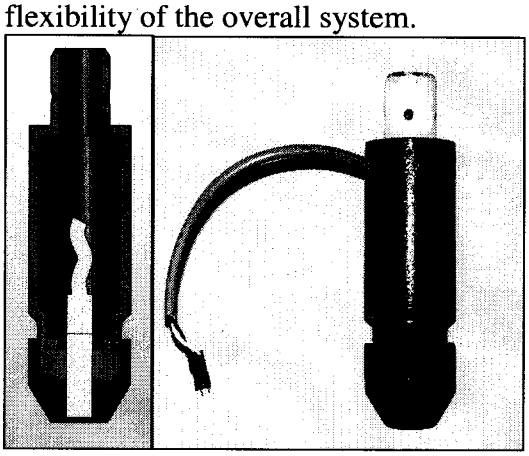

Figure 6. The LED task light is held in the collet tool

Palm-Cam

The axial camera in this tool is used for inspection or as a third viewpoint for 3D data collection. With a 512 column by 492 row and 256 levels of gray, the "bullet-style" camera collects images of similar resolution as the main stereo cameras (see below).

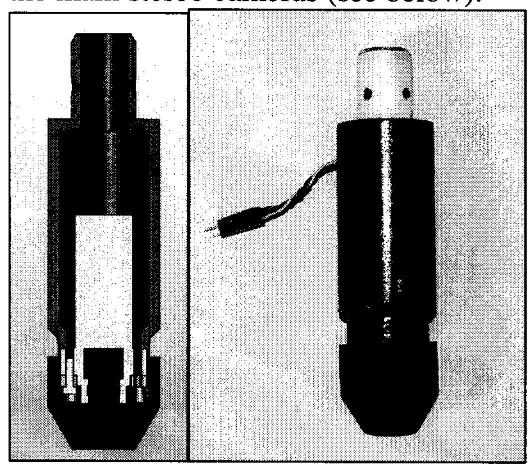

Figure 7. The "bullet" camera is held in a modified collet tool

Rotary Driver Tool

Currently the most sophisticated LEMUR II appliance, the rotary tool incorporates a driver shaft with a chuck that matches that of a standard Dremel tool. It can therefore be reconfigured to perform a variety of tasks similar to that of a Dremel tool, as well as to torque fasteners using a specially modified hex bit. It is for this last task in particular that a reaction torque sensor has been incorporated into the tool. Moreover, in keeping with the highly integrated nature of many of the LEMUR components, the torque sensor (an OEM unit manufactured by Futek) also serves as the body of the tool.

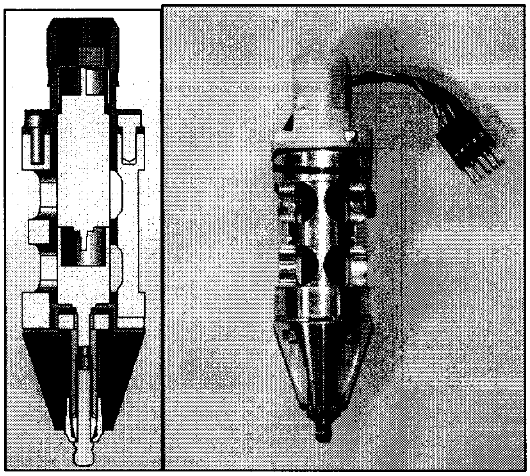

Figure 8. The driver tool has reaction torque sensing and can use any Dremel bit

Gripper

While not yet built, we intend to design a gripping tool for LEMUR II that will allow it to both grasp payloads and grip substrates during movement. Significant simulation and analysis will be performed to ascertain the needed complexity of such a gripper, particularly the need of additional degrees of freedom in a wrist/ankle assembly.

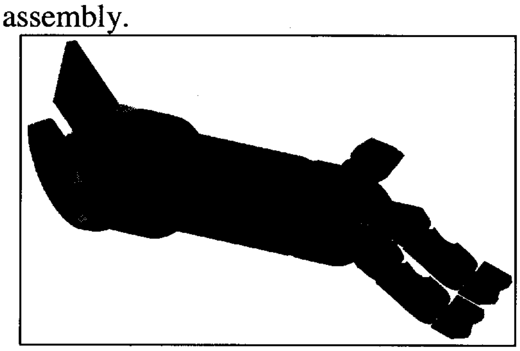

Figure 9. A gripper tool will be designed in the coming years

Vision System

Cameras

The front hazard avoidance cameras are a stereo set of black-and-white cameras each with a field-of-view of 112° horizontal by 84° vertical. They are tilted at a 30° down angle in order to give a view in front of the rover out to about 2.5 meters. The images are digitized at a spatial resolution of 640 columns by 480 rows and with 256 levels of gray. The camera frame itself is modifiable to provide different baselines (currently 12cm) and vergence (currently 5°).

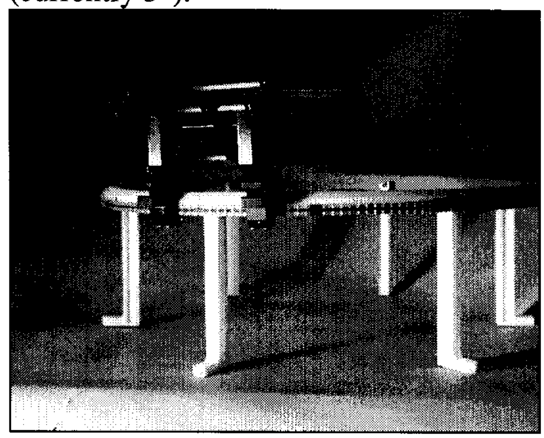

Figure 10. The stereo camera provides omnidirectional 3D data

Track System

The stereo set is mounted to a carriage that is propelled around the circumference of the body on a circular track. Rather than use a DC brushed motor as is done in the remainder of the robot, an ultrasonic motor was chosen, primarily for its low mass, lack of need of a geartrain, and self-braking capability. Feedback is performed by an encoder mounted to the carriage and by a pair of Hall Effect sensors that read a two-bit magnetic code created by magnets placed 120° apart on the track ring.

Electronics Stack

Electronics description

The LEMUR II electronics suite is derived from JPL's FIDO rover electronics architecture. FIDO serves as the flagship vehicle for a rapid prototyping team environment geared toward test and proof of new flight related concepts. The FIDO electronics architecture is designed to provide a research vehicle of great stability, reliability, and versatility. A variety of expandable I/O options permits ready integration of instruments, devices, and sensors as independent modular units. Separating electrical functions onto independent circuit boards facilitates simple and modular software interfaces.

Since the LEMUR II electronics suite retains the essential FIDO electronics architecture, the design and build was completed at an extremely low level of hardware and labor expense. By employing the same hardware, it utilizes the same software interfaces, housekeeping routines, etc. This further reduced manpower overhead to algorithms specific to LEMUR II.

Nearly all of LEMUR II PC104 boards are commercial or are commercially available boards that have been developed for FIDO. This means that researchers may work independent of the robots, treating their technology as a modular stand-alone unit that can plug into a robot with minimal integration.

A custom actuator driver circuit board was developed for LEMUR II to meet power and mass constraints. The board is capable of driving 12 motors simultaneously under computer control and is built on a standard PC104 footprint. True to flight application development, the board is built around the LMD18245, an off-the-shelf version of a chip designed specifically for use in robotic spacecraft.

The design includes several user- and system-friendly features. Two independent inputs for panic buttons or watchdog functions permit manual, computer, or watchdog disable of any one or all boards, without affecting the computer. An independent circuit holds all actuators inactive until the computer sends an enable signal. A single switch overrides all functions to allow manual control. Lights, test points, and outputs enable both the user and computer to independently monitor the state of the board and internal circuit functions.

<u>Electronics Suite Summary Outline</u>

- **Computing Stack PC104+**
  - CPU Board: Pentium, 266 MHz, PCI and ISA bus, 8 to 128 MB RAM
  - Solid State Disk
  - Ethernet board
  - Color frame grabber (2)
  - Digital I/O board
  - Analog input board
  - Analog output board
  - Quadrature Decoder boards (2)
  - Actuator driver boards (3)
- **I/O Available** (*Expandable)
  - Digital I/O: 96* channels
  - Analog Input: 16* differential channels, 12 bit resolution through filter boards
  - Filter boards: * differential or single-ended input, 2 pole low pass hardware filtering, 16 channels per board, multiplexed.
  - Analog Output: 32* channels
  - USB: 2 ports
  - RS232/422 serial I/O: 4 ports
  - Parallel: 1 port
  - Video: 8* color channels, NTSC
  - Quadrature Decoder: 30* channels, 16 bit per read

- **Power System**
  Raw bus power of 24 volts nominal is provided by lightweight high-energy lithium ion cells, which are hot-swappable, or by a tethered power supply.

Software Architecture

LEMUR II's core control software is derived from legacy FIDO rover software technology and provides robust, layered control architecture. This architecture has evolved over the past 5 years and has been successfully used on various heterogeneous platforms (SRR, SRR2K, FIDO, etc.) developed at JPL. The software architecture consists of the three layers shown in Figure 11, which themselves are built from modular components. This arrangement allows for the seamless removal and replacement of components with great ease.

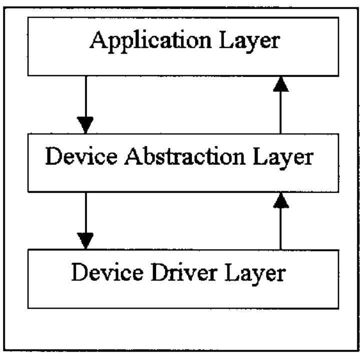

Figure 11. Division of layers in the software architecture

All device drivers in the Device Driver Layer are implemented in ANSI C. Because of the nature of real-time systems, each device driver execution time was carefully measured, and code was optimized to get maximum performance. Also, to improve reliability and remove any unexpected errors, each device driver code was tested functionally and structurally. LEMUR II's PC104+ stack has two buses: ISA and PCI. Most of the device drivers are on the ISA bus except for Color Frame Grabber and Network Controller. Each device driver exports its functionality through a xxx.h file to the Device Abstraction layer.

The Device Abstraction Layer combines and abstracts the Device Driver Layer functionality from the rest of the system. Low-level PID motion controller, motor and group queues, coordinate system, limb controller, motion prediction and timeout controller are implemented in this layer. Each Device Abstraction function exports its functionality through a xxx.h file to the Application Layer.

The Application Layer provides interface from high-level control of the robot to the outside world through a set of commands. A user can create and send a sequence of commands to the LEMUR II by using the Robot User Interface (RUI). By using a different set of sequences one can direct LEMUR II to do different tasks. In this way, there is no restriction to how high-level control should be implemented. For example, the walking algorithm for LEMUR II is implemented as a Push Down automaton. In the other robots from the Planetary Robotics Lab we have successfully developed behavior-based controllers by using the same constructs, again showing the flexibility of the system.

LEMUR II runs the VxWorks 5.3 real-time operating system on a PC104+/266Mhz Pentium processor. The VxWorks operating system loads directly from a solid-state disk. LEMUR II software is implemented in ANSI C language.

Motion Control

In this architecture motion control is done by software, which is a critical design choice. By having access to encoder counts, D2A, and robust low-level control architecture one can write any controller and seamlessly integrate it into the architecture to perform motion.

For low-level control LEMUR II is using a PID controller and a trapezoidal profiler to perform its motion.

The *Command Processor Task* is responsible for receiving and executing command sequences send by the Robot User Interface. This process runs at 1Hz communicating motion commands either to the *Continuous Sequencer* or to the *Motion Controller Tasks.* The *Continuous Sequencer* is a 10Hz hard periodic task. This task monitors motion queue buffers and also performs continuous sequences initiated by the *Command Processor Task.* The *Motion Controller* is a 200Hz hard periodic continuous task. This task reads encoder counts, computes velocity and distance of each actuator, and then runs a PID velocity controller to compute new D2A values for each actuator. This process is laid out in the block diagram in Figure 12.

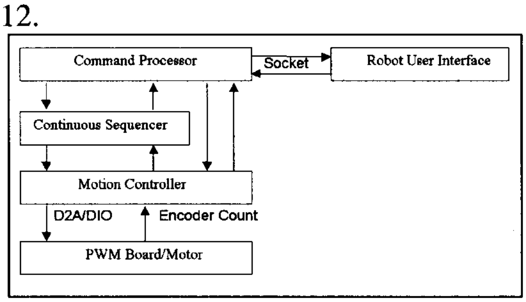

Figure 12. Information flow for motion control

Vision-Based Navigation and Manipulation

Consistent with the system-level emphasis of the LEMUR program, two algorithms related to navigation and manipulation have been developed on the LEMUR I platform and will be ported to LEMUR II.

Hybrid Image-Plane/Stereo (HIPS)

HIPS is a vision-based manipulation technique developed to enhance positioning precision beyond the limits of typical calibrated stereo methods. Consider first the typical stereo manipulation process. A model relating the 3D position of points to their corresponding 2D image-plane coordinates is generated for each camera by identifying locations on a calibration fixture. Using these models the 3D range to an identified target then can be determined via stereo correlation and triangulation. From this 3D range information, the joint rotations that position the manipulator at the desired location in 3D space are determined using the arm's inverse kinematics.

The difficulty associated with the typical approach is that sources of error in the stereo system and manipulator kinematics tend to accumulate which ultimately reduce positioning precision. Such sources of error include uncertainties in manipulator link lengths, joint position uncertainty and accurate knowledge of the transformation between the stereo reference frame to the base frame of the manipulator combined with uncertainties in stereo calibration and ranging. Additional sources of error result from a decline in calibration fidelity due to changes in the system configuration as a result of environmental factors such as vibration and thermal expansion.

By contrast the basic principle of the HIPS technique is the generation of camera models via visual sensing of the end-effector and the subsequent use of these models to drive the end-effector to a target without regard to any "real" reference frame. The camera models are generated by acquiring samples of both the image location of a visual "cue" on the end-effector and the joint positions at a series of pre-defined poses. It should be noted that such manipulator-generated camera models may be very different from those generated via a calibration fixture. However, the models accurately reflect the relationship between the position of the end-effector via the nominal kinematic model and the image-plane appearance of the end-effector in each camera.

Upon generating the models the 3D range to a target is determined using stereo correlation and triangulation. The joint angles that achieve this goal then are computed via the same kinematic model used to generate the camera models. Thus, this technique accounts for kinematic uncertainties such as link lengths and separate camera and manipulator frames in the typical approach. However, stochastic uncertainties such as "cue" detection resolution, joint angle knowledge, etc., remain unaccounted for so far. Therefore, the camera models are updated with additional joint and image samples throughout the manipulator trajectory to further refine the models in the target vicinity.

Figure 13. LEMUR I demonstrates a peg-in-hole task using HIPS

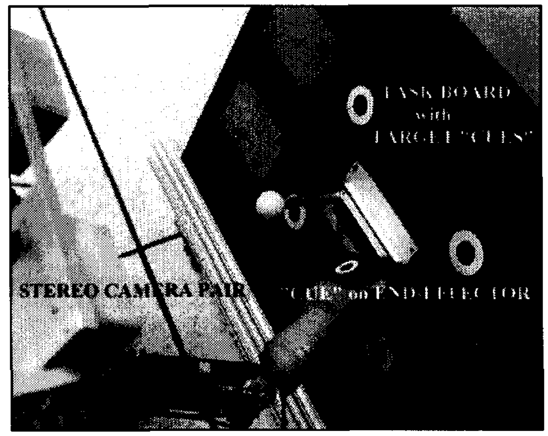

Figure 14. A close-up of the preceding figure

Barcode-Based Orientation and Information Transfer

The purpose of barcode algorithm is two fold. First it recognizes the barcode and reads out the part ID imbedded on the barcode. Second, when the four corners of the barcode are identified, the algorithm computes the pose of the rover with respect to the template for rover localization.

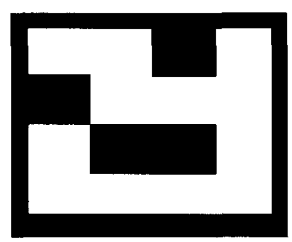

Figure 15. An example of the 16-bit barcode fiducial

The barcode is a simple 4 by 4 grid (Fig. 15). In order to keep the orientation of the barcode, the bottom border is thicker than other three borders.

An edge detection (Canny) algorithm is applied to the image (Fig 16a,b), and all straight lines are extracted from the edges. Because of noise present, many edges might be broken. Another algorithm is used to stitch the broken edges together. Once a straight line is extracted, an optimization algorithm is applied to determine location.

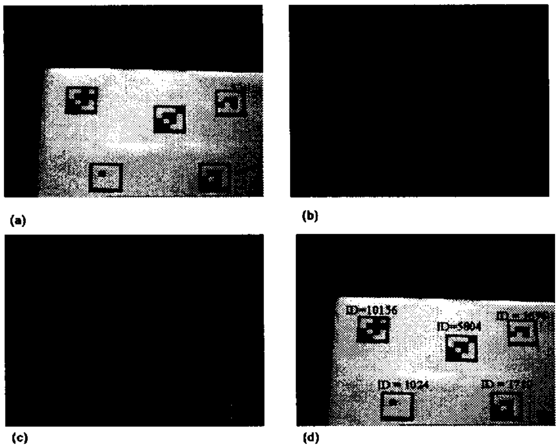

Figure 16. An example of the barcode decoding algorithm. (a) shows the original image; (b) is the edge image; (c) is the extracted border; (d) is the decimal ID of the binary code

In order to detect multiple barcodes present in a single image, we use a spatial grouping algorithm, which attempts to identify all edges from a single barcode and group them together. Within each group, its mass center is computed. Then the four border edges of the barcode are found. Fig. 16c shows the border edges detected by the algorithm.

When the four border edges are extracted, the four corners of the barcode can be determined by computing the intersection between the two correspondent border edges. With the four corners, we are able to locate the center of each grid approximately

At each center point, an average image intensity in a 3 by 3 window is computed and the value is used to judge whether this grid is black (1) or white (0). Fig 2.d shows the read out IDs printed on the five barcodes.

When the global coordinates of the four corners are known, the camera pose as well as the location of the rover can be determined. This work can be done by any well-established pose estimation algorithm.

Acknowledgements

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