LEMUR: Legged **E**xcursion **M**echanical **U**tility **R**over

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Abstract. Although future orbital facilities will have immense scale, details will require intricate operations in restrictive, confined quarters. LEMUR is a small, agile and capable six-legged walking robot that has been built at the Jet Propulsion Laboratory to perform dexterous small-scale assembly, inspection and maintenance. It is intended to expand the operational envelope of robots in its size class (sub-5kg) through the flexible use of its limbs and effectors, as well as through the modular changeout of those effectors. In short, LEMUR is intended as a robotic instantiation of a six-limbed primate with Swiss Army knife tendencies.

LEMUR's layout consists of six independently operated limbs arranged in two rows of three. The front two limbs have four active degrees of freedom while the rear four limbs have three each. Each limb is reconfigurable to allow the integration of a variety of mechanical tools.

1. General Design Problem of Robots for Orbital Facilities

LEMUR has been designed in response to requirements presented by NASA's Space Solar Power (SSP) project. In general, those requirements are driven by the fully robotic assembly, inspection, and maintenance (AIM) of a geo-synchronous space station of immense scale (~1600 space shuttle payloads). While several different robotic platform types will certainly be needed for the breadth of tasks on station, each platform must be as functionally flexible as possible to economize on volume and mass (and therefore, money). In LEMUR's case, the subset of operations chosen for development is characterized by being small-scale (sub cubic meter workspace) and requiring dexterity.

2. Implementation Overview

Representing an existence proof, the primate model of multi-mode limbs (particularly mobility and manipulation) with tool-using capability clearly provides a design path. However, the arrangement of the limbs in respect to the body was not so easily determined. Looking only at the requirements of the flight model, the lack of gravity becomes a paramount consideration. On earth, the closest analog to this environment is the sea. As the robot is intended to move along the surface of the structure, inspiration was taken from multi-limbed, dexterous sea creatures that tend to move along the bottom and among rocks. Immediately applicable examples are octopi and starfish. In terms of body layout, these creatures are notable for their axi-symmetry. Moreover, the creatures' limbs are long relative to body size. Many of the advantages of such a body plan are obvious. Being axi-symmetric, direction becomes less important, saving operationally expensive movement to face a particular direction for mobility or manipulation. In fact, with a judicious sensor layout, a robot could be designed to have even less directional preference than axi-symmetric animals do. Also, the long limbs generate a generous workspace. A less obvious advantage of axi-symmetry and long limbs is that any combination of limbs can be brought to bear on a workpiece. A system designed with these ideas in mind might look like the robot in Figure 1.

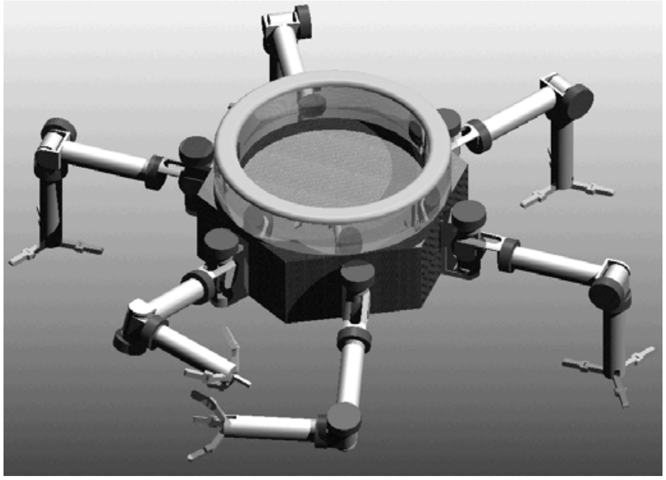

Figure 1. LEMUR-class robot designed for microgravity

While LEMUR's descendants would be asked to work in micro-gravity, LEMUR itself needed to work in earth gravity. (Creating a neutrally buoyant robot for underwater tests was too expensive). As such, its design could not necessarily use the same inspirations as a LEMUR-type robot for space. In fact, the necessity of supporting the body weight during movement was the greatest driver. LEMUR, like most mobile robots, was intended to move slowly enough to be quasi-static, requiring at least 3 contact points at any time. In particular, it was assumed to walk using an alternating-tripod gait similar to walking insects. Such a gait suggests a dual row of three in-line limbs as shown in Figure 2. A multiple-contact mobility mode is markedly different from the reach-and-grab or swinging gaits that would be possible in micro-gravity. These demands created a body plan that has more in common with an insect than a primate or octopus.

However, many things about LEMUR still adhere to the primate-based idea. To achieve an insect walk, each leg need only have 3 active degrees of freedom. However, a robot that dexterously manipulates objects needs more sophisticated articulation. To be more cost effective, and given the body plan, it was decided to use only the front limbs for manipulation. These limbs were given an extra degree of freedom (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 mounted to the front of LEMUR as well as more flexibility within the workspace.

As an aside, the philosophy of modularity and flexibility extends to the electronics and software as well. Both systems are packages adapted without significant change from other robots built by the Planetary Robotics Lab at JPL. As testament to those characteristics, the other robots are wheeled, not legged, and use from 3 to 6 wheels.

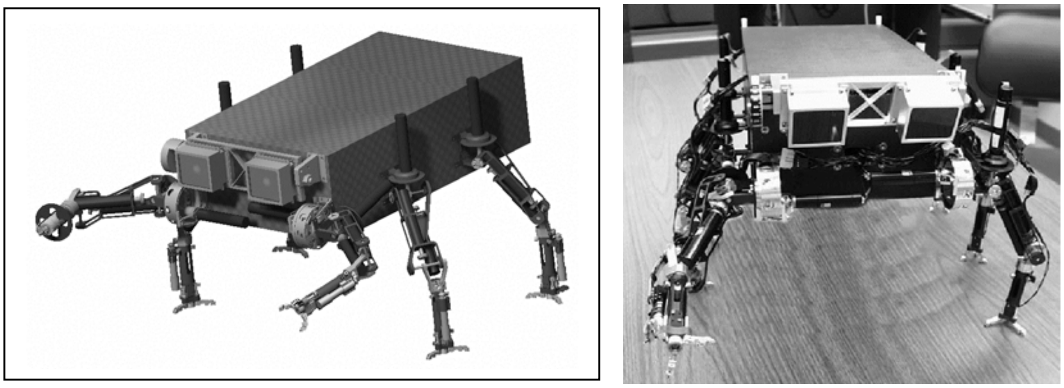

Figure 2. LEMUR in manipulation configuration

3. Limb Design

The limb design was dictated by several factors. First and foremost, every effort was made to decrease the overall mass of the limbs. LEMUR was intended to be a low-mass robot, and any unnecessary mass in a limb would be multiplied by six. Secondary to the mass consideration was a desire for as simple a mechanism as possible. Therefore, tendon systems were discarded in favor of direct drivetrains. Given the generally hard and inflexible (literally) technologies that are readily available for space-flight relevant systems, a tendon drivetrain would tend reduce the range of motion of anterior joints due to the mechanical overhead of passing tendons through to distal joints. Finally, the limbs needed to incorporate whatever structure was necessary to allow a quick change out of the end effector. The resulting limbs are quite simple in their kinematics. Key to this simplicity is the creation of a kinematically spherical shoulder joint for the front limbs. 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. Kinematically speaking, these shoulders are analogous to the ball-in-socket shoulder found in most endoskeletal animals.

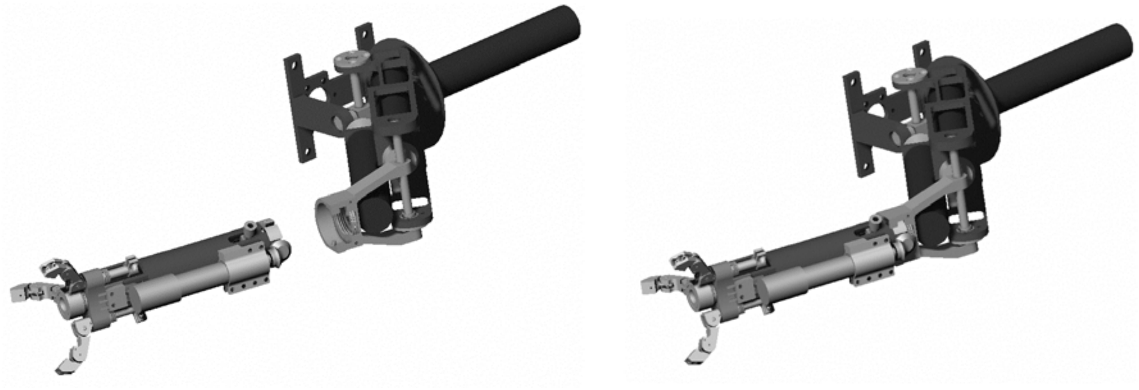

Figure 3. **Tools attach at the spring-loaded quick-connect**

An innovation the limb design is the inclusion of a quick-connect for tools. While quick-connects are commonplace in industrial robotics, they are a novelty in a system as small as LEMUR. The techniques used for industry are not applicable to LEMUR due to size or the reliance on fluid-powered (usually air) connectors. LEMUR’s quick connect is a simple bayonet-style connection that is spring-loaded to both lock the tool in place and eject the tool when the tool is twisted to the release point.

4. Tools

LEMUR has been equipped with two different tools to date. The standard tool is a gripper with three digits. Each digit is composed of three parts. The distal links are analogous to the phalanges of our own hands, though there are two rather than three per digit. These links are joined to another part that, in conjunction with the "palm", act as a carpal bone. The part rotates about an axis perpendicular to the knuckle axes, constrained within the wrist/palm of the gripper. It is this joint that allows the passive grip change. In the human hand it is most like the action of the joint between the metacarpal of the thumb (the first metacarpal) to the corresponding carpal (the trapezium). This joint is responsible for changing our hands from a hook grasp any of the other grasps that utilize an apposed thumb. As the joint in the gripper is self-centered by a torsional spring, the plane of action of each finger is 120° from its neighboring finger. However, upon contact with an object, the plane of action is forced to be perpendicular to the surface the finger has contacted. This compliance results in the passive grip change.

Figure 4. Gripper foot open, in the ball grasp configuration, and in cylinder grasp configuration

Unlike the limb joints, the joints of the gripper have only a relatively limited range of motion. This fact, coupled with the extremely small size of the foot, drove the design toward the use of tendons. For mass, volume, and complexity considerations, the gripper is actuated by only one motor. That motor drives a lead screw through a spur gear drive. Flexor tendons anchored to the fingers are attached to a yoke coupled to a nut on the lead screw. In order that the gripper can open, spring-loaded extensor tendons are also included.

The rotary tool has two main elements. The first is a foot surface on which LEMUR can walk, and second is a driver tool that can be used to tighten or loosen standard fasteners. As shown in Figure 5, the foot surface can be moved along the length of the tool. Moving the foot out of the way during tool use allows the cameras to view the ball-fastener insertion, the ball end to be easily inserted into the fastener, and the tool to be used on fasteners in tighter spaces. Like the gripper, all of the action of the driver tool is performed by only one motor.

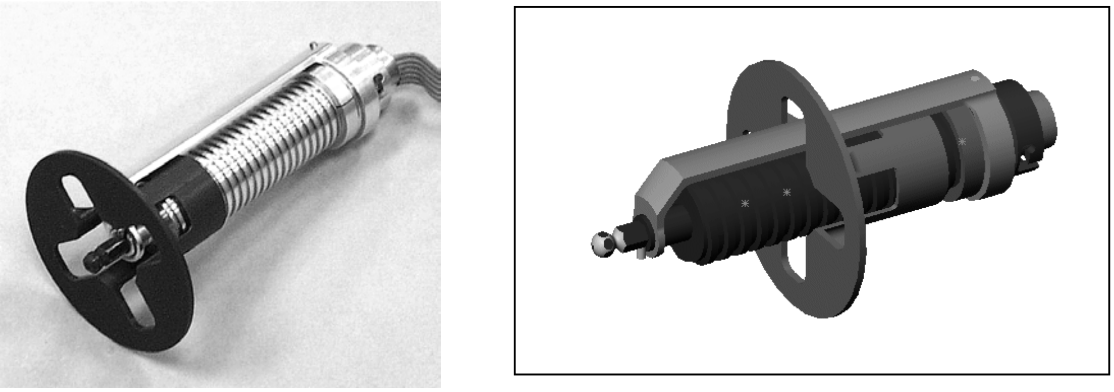

Figure 5. A close-up of the driver hardware in mobility and manipulation configurations

5. Sensors

The primary external sensor system is the stereo set of black and white cameras mounted to the front of the body. Images taken by these cameras are combined in software to create a 3D model of the world around LEMUR for autonomous operation. In addition, the positioning of the cameras relative to the front limbs in manipulation mode approximates the layout of human eyes to arms, which should prove advantageous for teleoperation during manipulation operations.

LEMUR's other visual feedback is provided by a "palm" mounted camera. LEMUR's small, low mass legs demand a very low mass and volume camera. To achieve this goal the camera fore-optics were designed into LEMUR's gripper foot and coupled to the imager/illuminator by a fiberoptic bundle. (Fore-optics are the lens arrangement at the entry point to a fiber-optic bundle). The mass of the fore-optic lens and fiber bundle is very small and therefore did not significantly impact the design of the foot and leg. This camera, like the stereo pair, can be used either for visual servoing (either of the gripper into which it is built or the other fore-limb) or for inspection. The idea for the placement of this camera owes a great deal to the idea of foot mounted sensors (primarily chemical) found in certain insects.

Figure 6. Full camera system with fore-optics incorporated into gripper tool

The main state sensors are the contact switches in the feet (providing a digital signal), digital encoders on every motor, and a three-axis accelerometer. Primarily used as tilt sensors, the triad can be used to help keep the robot body level during operations.

6. Biology and Space Robotics

Unlike other robotic systems that seek to explore and understand biology and engineering together, LEMUR's origins lack any necessary biological elements; biological elements are used exclusively as a design tool. As such, LEMUR, both in current and future forms, is free to take influence from any appropriate source. This freedom has resulted in elements culled from various animals, notably primates, insects, and octopi. Also, some of LEMUR's features are generalizations of natural designs, either in form or function. This design philosophy is powerful because it allows the broadest pallet of tools for the designer.

Another interesting aspect of LEMUR's design is the dichotomy between its features that are homologous to those in nature due to the strictures of physics (stereo eyesight and stereo machine vision) and those features that are divergent due to differences between human technology and natural technology (linear pull muscles and rotory motors).

7. Acknowledgements

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Figures

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