A STEWART PLATFORM LUNAR ROVER

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Abstract

A lunar version of the Robocrane is being developed at the Robot Systems Division of the National Institute of Standards and Technology (NIST) to address the needs of NASA researchers. The NIST robot, called ROBOCRANE, has three-pairs of rigged legs instead of actuators to create a gantry. The legs are joined in a Stewart Platform configuration providing a means for canceling out rotations normally present in gantry structures. Therefore, the frame can be made lightweight and yet, withstand high forces and torques limited mainly by the compression/tension strength of each leg. Each of three six foot legs rotates about an upper triangle to provide stable, yet flexible three-point ground contact. This makes an ideal configuration for attaching vehicles to the gantry for mobilization.

The unique structure of the NIST Robocrane provides a powerful platform which can accommodate the execution of diversified tasks due to its exceptionally high payload to vehicle mass ratio, ease of payload manipulation, outstanding mobility characteristics (tested on a smooth surface), and compact packaging for transport.

A 2-meter and a 6-meter version of the Robocrane have been built and critical performance characteristics and control methods analyzed. This robot, being able to rotate the legs independently about the upper triangle, is well suited for traveling over rough terrain and doing work such as construction or soil sampling on other planets. In 1992, the 2-meter Robocrane was exhibited at the Lunar Rover Expo, at the National Air and Space Museum, Washington, D. C.

Introduction

A new crane design utilizing six cables to suspend a load platform was first developed by the National Institute of Standards and Technology (NIST) in the early 1980's. A NIST program on robot crane technology, sponsored by Advanced Research Projects Agency (ARPA), produced the design, development and testing of three different sized prototypes to determine the performance characteristics of this proposed robot crane design. A description of the overall ARPA program and the results of this research are presented in [Dagalakis, 1989]. Initial testing of these prototypes showed that this design results in a stiff load platform [Dagalakis, 1989; Unger, 1988]. This platform (see figure 1) can be used in typical crane operations, or

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as a robot base, or a combination of both. Applications of this new crane design are illustrated: in [Albus, 1993] for the construction industry and in [Bostelman, 1993] for the subsea arena. As part of the research being done on the Robocrane, the authors have applied this unique system design to a Stewart Platform type mobile robot with potential lunar capabilities.

The objective of this paper is to describe the 2-meter Robocrane, including: the mechanical structure, the electrical components, computer and it's interface to sensors, the mobility control algorithm, the future lunar configuration and deployment scheme and various lunar applications.

A number of advantages of the Robocrane as applied to potential lunar rover applications are: rigid support and precise maneuverability of large loads, remote positioning of tools and equipment, execution of precise motions with tools/equipment to accomplish complex tasks, high lift-to-weight ratio, resistance to environmental perturbations (i.e.. wind, etc.), accurate control of loads via remote control, long-range mobility, and self-deployment.

A three wheeled vehicle was chosen over a four wheeled for several reasons:

1. Simplicity -- A rigid three wheeled vehicle will conform to an uneven surface. A four wheeled vehicle must have independent suspension to conform to an uneven surface.
2. Weight -- A three wheeled vehicle must be larger than a four wheeled vehicle to have the same stability against tip-over. However, the additional weight required for a fourth wheel with its suspension and drive train is greater than the additional weight required for the larger frame.
3. Stability -- A three wheeled vehicle is more stable against tip-over than a four wheeled vehicle of the same weight, if one wheel is kept down-hill.

Figure 1 - Photograph of the 2 meter ROBOCRANE Model with Camera Platform.

This design maximizes the wheel base for stability against tip-over, maximizes the wheel diameter to enhance traversibility, and maximizes the payload/vehicle weight ratio for mission effectiveness. With coordination of the three wheels and a work platform, the robot can change it's configuration enough to route through underpasses and straddle trenches. By changing the gantry shape and/or maneuvering the work platform, the robot can shift it's center-of-gravity to maintain equal ground pressure and to aid in hill-climbs.

This paper includes preliminary design and development of a Stewart Platform Lunar Rover, mobility control of the flexible structure, the deployment scheme from the Artemis lander, and a conclusion followed by a list of references for the paper.

Preliminary Design and Development

Figure 1 shows a photograph of a 2 meter Robocrane model used as a research tool to study the mobility and capabilities of such a system. The main components of the model are the mobile gantry, the work platform, the control computer and electronics, and the communications.

The mobile gantry consists of 2 m tubular aluminum frame components joined in the shape of an octahedron. The legs are triangles and attach to an upper triangle with loosely fit U-bolts to provide a hinge for the leg. Provided no leg-to-leg connections are made, the legs are free to rotate more than 180° with the vertical. Since small vehicles were chosen to show a construction application, truss cables and springs were attached to the legs and upper triangle to eliminate vehicle side loads. Each of three vehicles is attached to each leg via a universal joint and a rotary joint. The "U-joint" allows each vehicle to independently conform to the terrain while the rotary joint allows each vehicle to rotate with respect to the gantry. The U and rotary joints are simply bolted to the tubular frame.

A rotary potentiometer is housed within each rotary joint and attached between the gantry and the vehicle. The rotary pot. is used to measure the vehicle angle with respect to it's corresponding leg. A linear potentiometer is attached between each pair of adjacent legs and near the top triangle. Therefore, large leg motions can be sensed with a small linear pot. which provides direct leg separation distance between two adjacent legs. Only these six sensors are used as gantry geometry feedback to the computer.

The gantry houses a cable-driven Stewart Platform that has a work volume limited to cable length, work platform size and upper triangle size. A pair of winches are mounted to each leg near the vehicles. The mechanical winch cables follow the leg up to a pulley supported by the upper triangle and down to the work platform.

Each vehicle houses power amplifiers, and relay circuitry to power both the vehicles and the winches. The vehicle tracks are individually powered by a separate amplifier that can be instantaneously switched to winch control by reconfiguring the amplifier resistor network. Power for the system is provided by a battery stack located on each leg.

The computer is mounted on the work platform which, provides additional weight on the platform, and provides increased platform stability while the robot is driving. Electrical cables from the computer and to all sensors and amplifiers are supported vertically before being disbursed to add weight symmetrically to the robot. Tools are attached to the work platform. Depending on what is suspended from its work platform, Robocrane can perform a variety of lunar tasks. Examples are: cutting, lifting and positioning, core sampling and drilling, and gripping, and inspection.

By attaching stereo vision and pan, tilt, and zoom capabilities to a camera platform, Robocrane makes a large exploratory robot. Fixing cameras to the work platform allows inspection at close range to the work sight.

Mobility Control of the Flexible Structure

On the two meter Robocrane are three model vehicles (tanks), located at the base of each leg, and controlled by an onboard computer. The operator, using a rotary pot and a joystick, commands rotational velocity and translational velocity of the Robocrane. The controller measures the leg spacing and orientation of each tank with respect to the Robocrane. Each tank tread velocity is computed so that the Robocrane moves at the commanded velocity and rotational rate while maintaining proper leg spacing.

The control is a two step process. First we assume each tank can move in any direction and compute a translational velocity that meets the operator commands and maintains leg spacing. Second, we compute tread velocity by relating the tank's lateral velocity to a rotational velocity. The algorithm requires only two gains. One gain relates shape error into velocity and the other gain relates a tank's lateral velocity into rotational velocity.

The first step is to compute a desired translational velocity for each tank, v_1, v_2, and v_3. The tank may or may not be able to move in the desired direction but that is left until the second step. Figure 2 [left] shows an imaginary triangle formed by the location of the three tanks. The length of each side is the desired length plus an error term. The operator commands a rotational and translational velocity, ω_{cmd} and V_{cmd}, for the structure represented in the coordinate frame x–y. A coordinate frame, ov-in, is attached to each vertex.

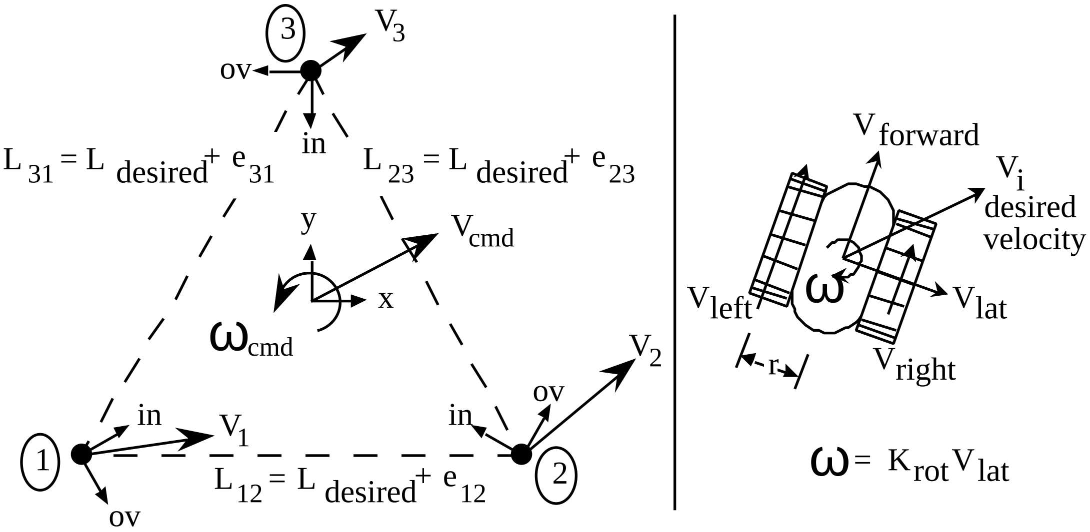

Figure 2 - [left] Imaginary triangle formed by the three vehicles used to compute velocities, rotations, and vehicle spacing. [right] Each tank can move forward and can rotate but cannot move laterally. Thus, the rotational rate is set proportional to lateral velocity in order to head the tank in the desired velocity direction.

The desired velocity for each tank is the sum of the velocities that translates the Robocrane at the operator's commanded velocity, rotates the Robocrane at the commanded rate, and maintains the proper tank spacing. To translate the crane, each tank should move at the commanded velocity, v_{cmd}, taking into account the different coordinate frames. To rotate the crane, each tank should move assuming rigid body rotation. For computational simplicity, we assumed small deviations from an equilateral triangle. Thus, to rotate at the commanded rate, each tank should move in its ov direction with a velocity:

$$v_{ov} = [L_{desired} / 2\cos(30°)]\, \omega_{cmd}.$$

Finally a velocity must be added that moves the tanks relative to each other in order to maintain the desired spacing. This feedback portion of the algorithm accounts for tread slippage, terrain aberrations, and inaccuracies in the control model. Each vehicle is commanded a velocity proportional to the spacing errors, e_{ij}, in a direction that drives the errors to zero. Each tank attempts to correct the two adjacent sides of the triangle. For tank 2, consider the case where tanks 1 and 3 are fixed and that the lengths L_{12} and L_{23} are directly controllable. For a first order response the change in length is set proportional to the error:

$$\frac{dL_{12}}{dt} = -K_{shape}\, e_{12}$$

and similarly for L_{23} . However, we do not have direct control over the lengths but rather we control the tanks' velocity. Therefore, shown in the equation below, the Jacobean is used to transform the changes in the length of the triangle's sides to changes in the Cartesian position of the tank. The commanded velocity for tank 2 becomes:

$$\begin{bmatrix} V_{ov} \\ V_{in} \end{bmatrix} = \begin{bmatrix} \left.\frac{\partial ov}{\partial L_{12}}\right|_{L_{23}} & \left.\frac{\partial ov}{\partial L_{23}}\right|_{L_{12}} \\ \left.\frac{\partial in}{\partial L_{12}}\right|_{L_{23}} & \left.\frac{\partial in}{\partial L_{23}}\right|_{L_{12}} \end{bmatrix} \begin{bmatrix} \frac{dL_{12}}{dt} \\ \frac{dL_{23}}{dt} \end{bmatrix}$$

Again, for computational simplicity, we assumed small deviations from an equilateral triangle. Thus to maintain the shape, the desired velocity of tank 2 in the ov-in coordinate frame become:

$$V_{ov} = K_{shape}\left(e_{23} - e_{12}\right)$$
$$V_{in} = \frac{K_{shape}}{2\cos 30^{c}}\left(e_{12} + e_{23}\right)$$

Similar equations are used for tanks 1 and 3. Note that each tank attempts to maintain the length of both of the adjacent sides of the triangle. If the tanks could move in the desired direction the side lengths would be adjusted at a rate proportional to twice K_{shape} .

For the second step the three velocities are added together for each tank yielding a desired velocity which, in most cases, will not be pointing in the same direction that the tank is heading. Each tank can move forward and backwards by driving the two treads in the same direction and each tank can rotate by driving the treads in opposite directions. However, the tank normally cannot move in the direction of the desired velocity (see Figure 2 [right]). One method to account for the misalignment between the heading and desired velocity would be to have the tanks stop, rotate to the proper heading, and then drive at the desired speed. The obvious problem with this is that the tanks would have to start and stop whenever the operator changed the commanded velocity or when errors occurred in tank spacing.

Instead the lateral part of the desired velocity is converted into a rotational rate, ω, that is proportional to the lateral velocity. The tread velocities are:

$$V_{left} = V_{forward} + r K_{rot} V_{lat}$$
$$V_{right} = V_{forward} - r K_{rot} V_{lat}$$

If the tank is moving backwards, $V_{forward}$ is negative, then the sign on the rotation is flipped so that the rear, rather than the front, of the tank turns in the direction of V_{lat}. Finally, if any tread velocity is greater than its maximum, then all the tread velocities are scaled proportionally to keep tread velocities within operational bounds.

Proposed Robocrane for Artemis Deployment

A NIST/Arizona University (AU) team proposed [Albus, 1992] a vehicle structure for a NASA Artemis lunar exploration mission that is very similar to the NIST 2-meter model ROBOCRANE except that it uses large diameter bicycle type wheels instead of tracked vehicles. The NIST/AU design would support a work platform carrying instruments by six cables from six winches located at the three vertices of the center triangle of the frame. The proposed three-wheeled lunar rover is to have a mass of 65 kg, including the vehicle and 15 kg of experiments and platform weight. This allows an increased payload of much more than the 15 kg payload being carried once deployed at its destination. The work platform would also support a mast (see figure 3) with three cables attached to its top. At the very top of the mast is a pan/tilt head supporting a narrow beam antenna that is kept pointed toward the Earth for wide-band

Figure 3 - Photo of a model of the proposed Stewart Platform Lunar Rover.

communications. Near the top of the mast, under the antenna dish, a suite of cameras is mounted for navigation, mapping, and driving.

The lengths of the three mast cables are controlled by three additional winches to put the mast in compression and thereby maintain all nine cables in tension at all times. This enables the work platform to be moved outside the footprint of the vehicle where it can perform experiments on vertical surfaces of boulders or cliffs.

The three additional winches applying forces between the gantry and the platform can also be used to exert sufficient downward force on the work platform to lift the entire vehicle off the ground. Additional force may be needed by attaching a work platform tool and inserting it into a surface, thereby lifting the vehicle from the work platform to apply additional weight. This capability is also used during vehicle deployment from the Artemis lander.

The vehicle will be folded up so as to fit on top of the lander inside a 2 1/2 meter diameter nose cone. Each of the three wheels will fold up inside its triangular wheel support structure, and the wheel support structure folds down so that it is in a vertical plane. When in their stowed position, the wheel forks are upside down with their tops resting on the top of the lander. During launch and transit, six cables between the vehicle and the work platform are tensioned so as to hold the vehicle firmly against the top of the lander.

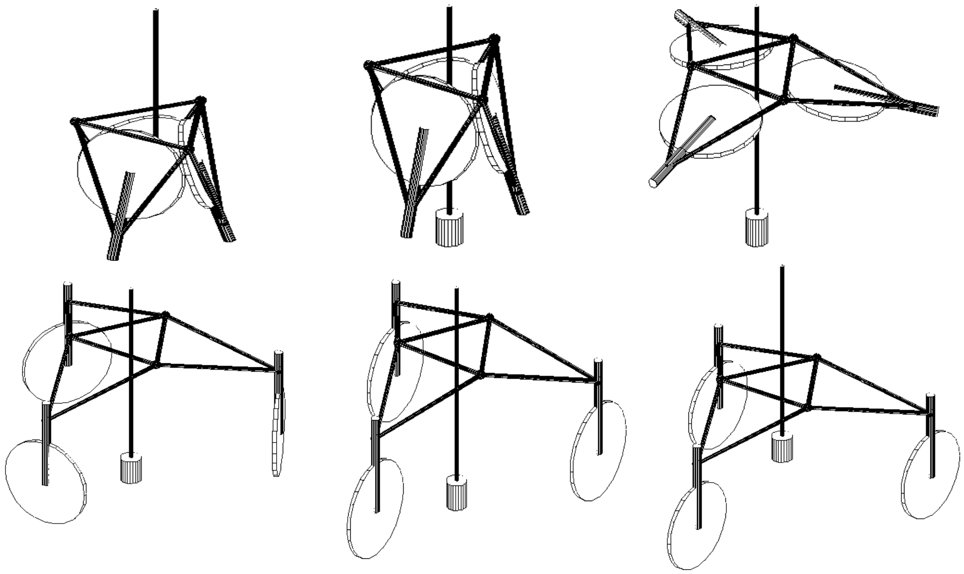

Figure 4 - Conceptual drawings of the deployment sequence from the Artemis Lander. (Cylindrical payload would be attached to the lander; cables not shown for clarity).

The work platform rests in the center on top of the lander, attached to a ramp that slides and pivots during the deployment phase. The deployment sequence consists of a series of six steps:

1. The six cables holding the vehicle in its stowed position are jettisoned.
2. The three mast cables are winched in, and the six cables attached to the work platform are let out under position control, so that the vehicle is lifted off the lander and supported in a stable configuration on the work platform.
3. A set of cables connecting the wheel axles to the lander are winched in while an opposing set connecting the wheel axles to the vehicle are let out. This causes the

wheels to swing down and the wheel support structures swing out. The set of cables connecting the tops of the wheel forks to the top of the mast are winched in so that the wheels drop down and the wheel support structures swing up into deployed position.
4. The cables attached to the wheel axles are jettisoned and the structural support cables attached to the top of the wheel forks are winched taut. At this point the vehicle's wheels are fully deployed and ready for launch.
5. The six cables attached to the work platform are winched in while tension is maintained by the three mast cables, so as to lower the vehicle.
6. The sliding ramp on which the work platform is resting slides to the side of the lander top.
7. The sliding ramp slides out over the edge of the lander and tilts so as to lower the vehicle to the ground. Once all three wheels are on the ground, the work platform is then free to roll away from the lander to begin its exploration mission.

The Phase One deliverables from the NIST/AU proposal are: to define mission and sub-system specifications for range, power, weight, communications, computing speed and memory, etc.; develop alternative designs of the vehicle on a CAD system; design and produce a full-scale physical mockup of the proposed vehicle and demonstrate technical feasibility of the vehicle design; design and produce a full-scale working prototype of the work platform, tool set, and simulated instrument payload, mounted on a stationary mockup of the vehicle; produce a report which describes the results of the Phase One study, and recommendations for Phase Two.

Conclusions

The Robocrane Stewart Platform Lunar Rover makes a large, lightweight, flexible, mobile, stable, and versatile tool for doing a variety of required tasks. Two feasibility models have been developed at NIST. Arizona University and NIST have produced a three phase proposal incorporating a deployment scheme, vehicle designs, and methods for:

1. Navigation and payload free-space manipulation accomplished through remote supervisory control based on the information obtained through cameras
2. Force controlled payload and tool contact manipulation accomplished through virtual reality teleoperation augmented by local reflexive sensory-interactive control
3. Computer-aided remote driving technology employed for driving, with collision and tip-over avoidance procedures activated by local reflexive sensory-interactive control.

Additionally, computations of rover power while traversing various simulated terrains and rover component failures are to be addressed.

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