The Development of Intelligent Robotic Systems with Practical Applications

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Abstract

This paper describes three current research activities that are ongoing at the Center for Intelligent Machines and Robotics at the University of Florida. The three projects are:

- the development of a Smart Kinestatic Interactive Platform (SKIP),
- the navigation of an autonomous vehicle,
- the development of an Articulated Transporter/Manipulator System (ATMS)

Common to all three projects is the computer control and automation of machines and mechanisms. This common theme is emphasized throughout the paper. Further, all three projects involve recent theoretical developments which have been applied and demonstrated in hardware. Hardware implementation serves to verify and refine the theoretical technique into a useful and workable system.

1. Introduction

The computer control of machines has been the focus of much research for the past thirty years. The advantages of such systems are obvious, i.e. improved accuracy and repeatability, continuous operation, and the removal of humans from potentially dangerous environments. This paper describes three such automation projects.

The first project involves the development of a unique parallel mechanism which incorporates force control. This development, named the Smart Kinestatic Interactive Platform (SKIP), is applicable to tasks where the system end effector experiences force constraints in addition to translational and rotational degrees of freedom. In addition, the mechanism is able to actively filter vibrations.

The second project described in this paper deals with the development of a fully autonomous vehicle which is able to plan and execute paths throughout its environment. Applications of such a system are numerous. The specific application of the system under development is to pull a bomb detection system across a range site to locate buried unexploded ordnance. Once these are located, a second autonomously navigating vehicle, i.e. an excavator, will move to the location and remove the buried munition.

The final project which is described in this paper is the development of a mobile vehicle which can cross ten foot gaps and move between planes that are vertically separated by a distance of twelve feet. The resulting design is a segmented vehicle which is comprised of twelve sections. Each segment possesses three degrees of freedom which allows the system to move in a snake-like fashion through its environment. The system under development is being fabricated for application to nuclear environments where the multitude of pipes and conduits requires a mobile transporter that can effectively move through this environment.

2. Development of a Smart Kinestatic Interactive Platform (SKIP)

A "platform" or "parallel mechanism" is defined as any mechanical device that has six legs that connect a moving platform to a base. This kind of mechanism possesses the desirable characteristics of high accuracy, high payload-to-weight ratio, and good static stability. To apply Kinestatic Control to these mechanisms it is necessary to first obtain accurate compliance models. These models can be readily determined for parallel mechanisms, provided that the position and orientation of the moving platform is known relative to the base. Therefore, the key and central task is to determine the position and orientation of the moving platform relative to the base given the sensed lengths of the six legs. This task is referred to as the forward kinematic analysis for the system, and for these kinds of mechanisms the simplest solution involves solving an eighth degree polynomial in a single variable.

As a point of reference, the geometrically simplest parallel mechanism has the structure of an octahedron, and it is designated as a "3-3 platform" since there are three connecting points on the base and three on the moving platform. The double connection points shown in Figure 1a produce a very simple geometry. However, there is a very serious mechanical disadvantage. It is not possible to design the necessary concentric ball and socket joints at each of the double connection points without mechanical interference. It is preferable to separate the double connection points and in this way to overcome the mechanical design problem.

In general, as double connecting points are separated, the complexity of the forward kinematic analysis for the platform increases. It should be noted that there are multiple solutions. This means that there are multiple closures of the mechanism and that there exist a number of different ways it can be assembled. Each assembly yields a different position and orientation of the platform while possessing the same set of six leg lengths.

It is, of course, possible to perform numerical iterations (an optimization using six independent variables) to obtain the position and orientation of the platform. However, it is well known that such iterative solutions have a tendency to "jump" from one closure to another. From a practical viewpoint, this is undesirable. It is far more desirable to derive a single polynomial in a single variable, the solution of which yields all possible locations of the moving top platform. The desired solution can then be extracted from this finite set of all solutions. Such a solution is said to be in "closed-form".

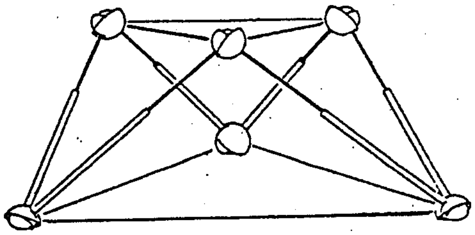


Fig. 1a: 3-3 platform

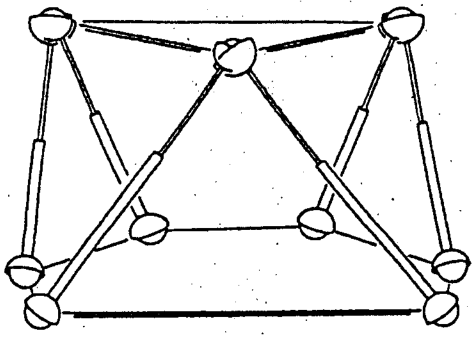


Fig. 1b: 6-3 platform

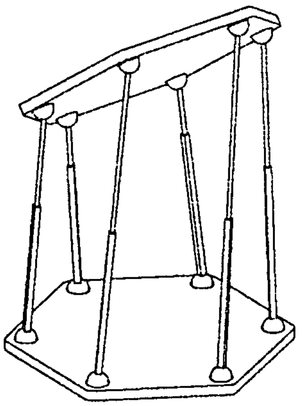


Fig. 1c: 6-6 platform

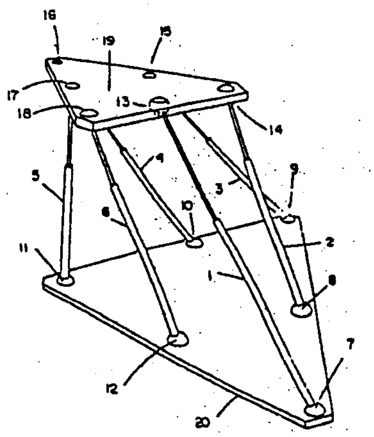


Fig.1d: Special 6-6 platform

It was only recently that the closed-form forward analysis for the geometrically simplest 3-3 platform was solved by Griffis and Duffy [1]. Briefly, an eighth degree polynomial solution was derived, and this has been extended to a 6-3 platform (Stewart's original platform), Figure 1b. It would be desirable to perform the forward analysis for a general 6-6 device (Figure 1c), however this is unrealistic. The closed form equation will be at least a 40th degree polynomial, which has been obtained for a similar device of lesser complexity [2], and this is computationally impractical for real time control.

As previously stated, the necessity for a simplified closed-form forward kinematic analysis (specialized geometry) manifests itself whenever the mechanism is to control force and position simultaneously. The requirements of specialized geometry and good mechanical design (no mechanical interference) is satisfied by a number of platforms. It is the union of the theory of Kinestatic Control and such platforms that yields SKIP.

The history of parallel mechanisms begins with the Stewart Platform (see Figure 1b, the 6-3 device) which is used in existing flight simulators. These simulators are currently produced by Link Corp. (U.S.A.) and Redifussion Corp. (U.K.). Flight simulators consist of a platform upon which the pilot rides. The platform is connected to a base by six legs. (Each leg is a SPS kinematic chain where S represents a ball and socket joint and P designates a sliding or prismatic joint which is actuated.) The pilot controls the pitch, yaw, and roll of the platform using a joystick. The analysis required to control the motion of the platform through space is relatively simple. Given successive positions and orientations of the platform, it is required to determine sets of leg lengths. This is the so called "reverse kinematic analysis" and for each location of the platform, there is a unique solution.

This technology is well established and has evolved over a period of some twenty five years since D. Stewart published a paper on such devices in 1965 [3]. It is common practice to call all platforms "Stewart platforms". However, Stewart's specific design is illustrated in Figure 1b, where it is designated as a "6-3 platform". (It can be seen that there are three connecting points on the platform, and six connecting points on the base.) Two new platforms have been invented by Griffis and Duffy, and a US patent has been allowed to the University of Florida [4]. A prototype of one of these platforms has been built (see Figure 2) at the Center for Intelligent Machines and Robotics at the University of Florida. The problem of controlling force and motion of the platform has been the subject of an NSF contract (co-PI's J. Duffy and C. Crane) entitled "A Geometrical and Experimental Investigation of Simultaneous Force and Motion Control of Robot Manipulators". This contract was awarded in December 1988 and it was completed in December 1991. Briefly, the task of controlling force and motion of the platform was accomplished by introducing compliance into the legs. A new theory called "Kinestatic Control" has been successfully developed and most importantly, this has not been a paper study. This novel theory has been verified experimentally in the University of Florida Center for Intelligent Machines and Robotics laboratory. Contact forces/torques between the robot end effector and the environment have been reduced to specified levels and even been nullified completely whilst simultaneously controlling the end effector motion. Two prize winning papers (Best Paper award by the American Society of Mechanical Engineers (Sept., 1990) and a nomination for Best Paper by the International Federation for the Theory of Machines and Mechanism (July, 1990)) have been published on the theory [5], [6]. This new theory constitutes the basis for the control of the prototype platform/end effector which is being designed under this effort.

The introduction of compliance into the legs of platforms that have a simple forward analysis enables one to control forces and motions simultaneously. Consider an application for the special 6-6 platform of Figure 1d where the movable platform is not always free to move and is required to come into contact with the environment. As a relevant application, consider the case where an airline maintenance crew must remove and replace a jet engine. This special device can be employed as a three-dimensional or spatial jack where the movable platform is carrying the engine. It is essential not only to control allowable motion but also to avoid damage by controlling contact forces and couples simultaneously when the engine comes into contact with the aircraft wing or fuselage. Such a platform is classified as a Smart Kinestatic Interactive Platform (SKIP).

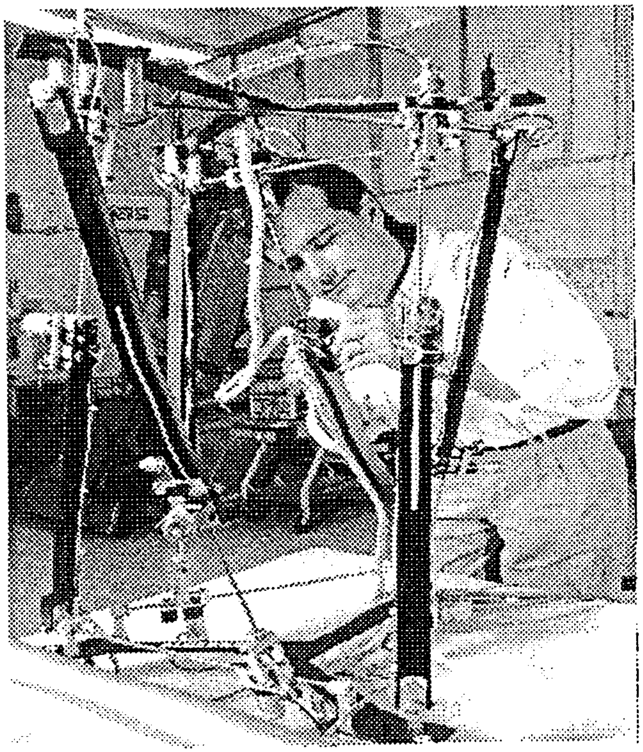


Fig. 2: Table Mounted SKIP

3. Navigation of an Autonomous Vehicle

There currently exist in the US many previously closed military installations, installations currently scheduled for closure, and operational installations encompassing areas that may contain buried/unexploded ordnance (UXO). These installations must be rendered safe by detecting and clearing the UXO. The hazardous conditions surrounding these operations not only inhibit manned operations, but also require additional manpower and equipment for backup support. Current manpower-intensive methods cannot safely complete the detection/cleanup/repair in a cost-effective manner.

The Air Force/Wright Laboratories construction automation/robotics program is involved in a tri-service effort to provide the necessary automation /robotic technology required to solve the range clearance problem. This technology provides a telerobotic means of executing peacetime range clearance as well as post-attack Explosive Ordnance Disposal (EOD) and operating surface repair and recovery during wartime. As manpower becomes more critical to the Air Force of the future, the benefits of unmanned ground vehicles (UGV's) to the peacetime range clearance and wartime base recovery missions become more obvious and important. The UGV can perform these missions in a dangerous environment while human operators and/or combat airbase personnel remain in a safe shelter.

The navigation problem statement can be simply defined. It is assumed that the current position and orientation of the vehicle is known. Further, it is assumed that boundary and known obstacle locations have been determined from a prior survey of the area. In this analysis, an obstacle is described by an n-sided polygon. This polygon may be concave and polygons may overlap. Lastly, a position to navigate to is specified, either by a human supervisor, or by a hierarchical control computer.

Based upon the given information, the objective is to (1) plan an efficient path to the goal, and (2) to then move along this planned path without driving into one of the known obstacles or striking an unexpected object (either stationary or moving) which may be in the area.

The navigation system is being designed to operate a robotic heavy equipment excavator (see Figure 3). The laboratory development, however, is taking place on a surrogate vehicle named the Navigation Test Vehicle (NTV) which is shown in Figure 4. Once the navigational algorithms are successfully tested on this platform, the sensors and software will be transferred to the excavator vehicle.

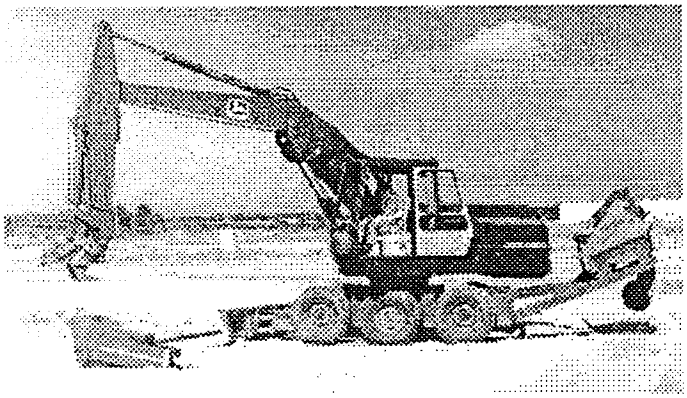


Fig. 3: Multi-Function Excavator

The NTV consists of a Kawasaki Mule which has been modified for computer control. Actuators have been placed on the four functions of (1) steering, (2) throttle, (3) brakes, and (4) transmission. Closed loop control is exercised on each of the four actuators via a VME based computer system which is operating under the VxWorks operating system.

Two important problems must be addressed if the vehicle is to successfully navigate to the goal. First, the vehicle must have some accurate means of determining its position and orientation. Without this knowledge, it is impossible to keep the vehicle on the previously planned path. Second, the vehicle must have some means of detecting objects that are obstructing its path. Once these unexpected obstacles are detected, the originally planned path must be modified to avoid this new obstacle.

The first problem of determining the vehicle's position is being addressed in two ways. An inertial navigation system named MAPS (Modular Azimuth Positioning System), manufactured by Honeywell, Inc., has been mounted on the NTV. This system communicates with the VME controlling computer via an RS-422 synchronous communications protocol. The MAPS can return the vehicle's position and orientation at a rate of approximately eight hertz. The MAPS system is currently being operated with a resolution of one foot in the North/South direction and of one quarter foot in the East/West direction. Tests with the unit show that an error of approximately two feet exists after the MAPS has been operational for four minutes.

The second means of determining the vehicle's position involves the use of a Global Positioning Satellite System (GPS). Wintec, Inc. of Ft. Walton Beach, Florida, is implementing a differential GPS system which will be mounted and tested on the NTV. Tests with the GPS system to date have shown that it can very accurately determine vehicle position (a resolution of inches) at a rate of approximately one hertz.

The detection of unexpected obstacles is currently being accomplished with ultrasonic transducers. An array of sixteen sensors are mounted around the NTV. These sensors have an effective range of approximately 7.5 meters and can all be fired and updated at a rate of three hertz. The ultrasonic sensors provide a basic obstacle avoidance capability. The range is not adequate for vehicle speeds in excess of five miles per hour.

Fig. 4: Navigation Test Vehicle

Other obstacle detection sensors such as laser scanners and vision will be investigated in the future for application on the NTV.

Currently, only the MAPS is mounted on the NTV to provide position and orientation information. Effective navigation of pre-planned paths has been accomplished by using the MAPS to support a "carrot navigation" approach. The controlling computer designates a point which lies on the pre-planned path as a "carrot". The NTV steering and throttle are controlled via a standard PID control algorithm to direct the vehicle towards the "carrot". Once the NTV approaches within approximately seven feet of the "carrot", the "carrot" is moved further along the path. If the ultrasonic sensors detect an unexpected obstacle, the "carrot" is moved to the right or left in order to avoid this obstacle and to avoid the a priori known obstacles.

This "carrot navigation" method has proven to be very straightforward and effective. It has allowed for modular software development in that navigation along the path or navigation to avoid unexpected obstacles are very similar.

The results of a sample test case are shown in Figures 5 and 6. For this case, the vehicle was commanded to move from a position of (0,0) and an orientation of 0 degrees measured from the X axis to a position of (100,100) ft and an orientation of 0 degrees. There were no unexpected obstacles during this test.

An off-line plan was generated to move the vehicle to the goal position. Figure 5 shows the output from the MAPS as the vehicle traverses along the path. It is interesting to note that the resolution of the MAPS (one foot in the North/South direction (y axis for this run) and one quarter foot in the East/West direction) is clearly visible in the figure.

Figure 6 shows the results of the steering control algorithm. The desired azimuth represents the angle from the current vehicle position to the "carrot". The

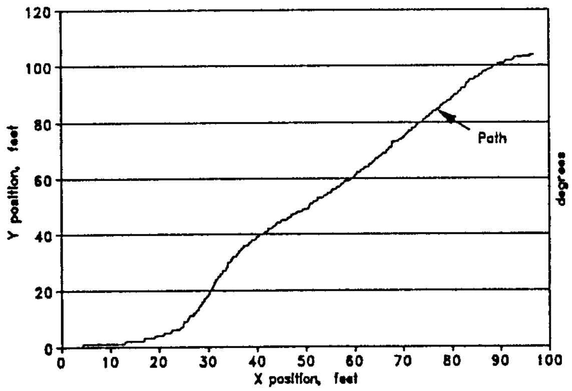


Fig. 5: Results- Position Output

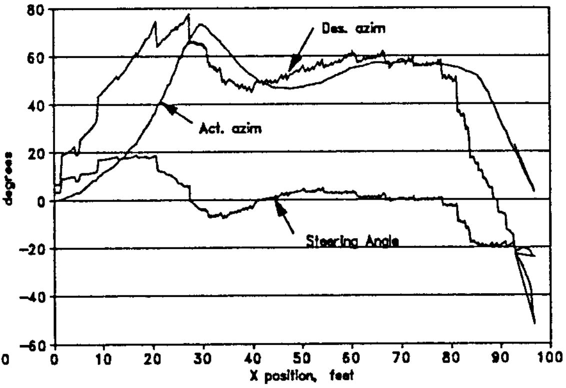


Fig. 6: Results- Steering Control

actual azimuth is data returned by the MAPS. The difference between the desired and actual azimuth represents the error that is being used to influence the steering angle. The actual steering angle is also shown in the figure. The discontinuities in the desired azimuth value occur when the "carrot" is changed to a position further along the path.

Future work on the project is aimed towards performing tests of the system when unexpected obstacles are present and integrating the MAPS and GPS navigation units. These tasks are scheduled for completion in late 1993.

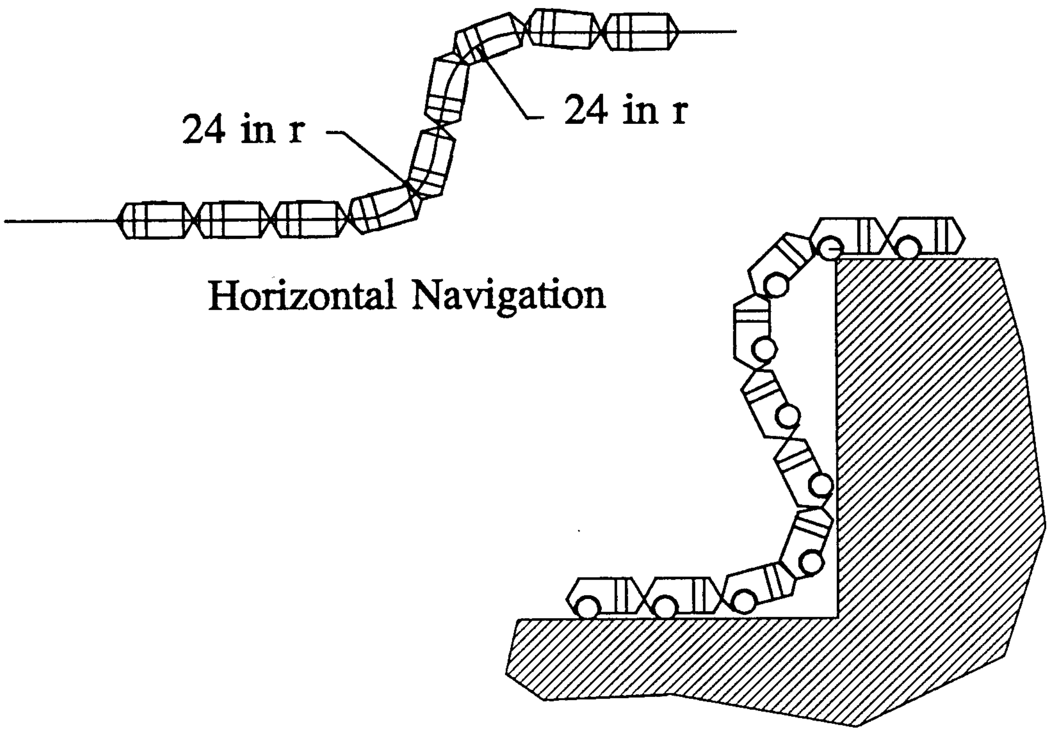
It should be noted that there are other missions, both wartime and peacetime, that lend themselves to application of the technology being developed under OSD/UGV program. Airbase fire fighting/ fire detection, hazardous waste handling/cleanup, and the automation of routine Air Force civil engineering operations are other areas that will benefit from this technology.

4. Development of an Articulated Transporter/Manipulator System (ATMS)

Articulated mobile robots have been examined with respect to their suitability and usefulness in the environment expected in a nuclear power plant [7]. These robots have typically had serially connected segments. A feature of the articulated structure is its ability to make large changes in elevation. This would be useful in avoiding obstacles and in changing floors in a nuclear power plant. The main drawback of this feature is the excessive joint torque necessary to execute useful vertical navigation. This leads to large, heavy segments, which in turn require more joint torque. Previous work with this sort of mechanism lead to an articulated mobile robot design [8] as illustrated in Figure 7. Actuator requirements for this design were outside the present technological envelope. Joint configuration between segments and actuation schemes were examined in an attempt to improve expected performance. This section of the paper describes the evolution of a serially connected parallel actuated joint scheme from concept to mechanical design. Attention is given with respect to the scheme's applicability to an articulated mobile robot.

Specifications were developed that are believed to meet the requirements of an articulated mobile robot in a nuclear power plant type environment. These specifications were used to evaluate several joint connectivity-actuation schemes qualitatively.

There are two modes of navigation for an articulated mobile robot. The first is horizontal navigation. The second is vertical-bridge navigation. These navigational modes impose limits and requirements on the robot.



Horizontal Navigation

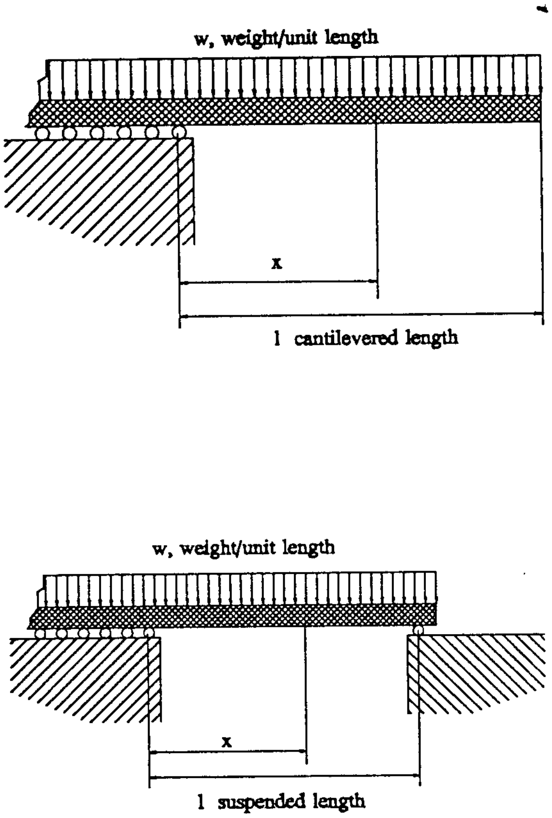
Vertical Navigation

Fig. 7: Previous articulated mobile robot concept

Minimum radius of turn: 610mm (horizontal nav.)
Ascend/descend 40 degree incline stairs (either or both)
Jump obstacles up to 1m (vertical nav.)
Change elevation: 3m (vertical nav.)
Bridge gaps: 3.6m (bridge nav.)
Navigate speed: 20m/min (horizontal nav.)

The navigational requirements are of importance in the design of the robot. They limit size and, along with size, set driving force/torque requirements. Speed requirements set ratios on wheels, tracks, or other locomotive devices. Vehicle weight and expected inclines set wheel driving torque.

Elevation change, gaps jumped, obstacles jumped, and vehicle weight set joint torques. For an order of magnitude estimation of joint torques required, simple static modeling of a structure with distributed weight was performed. Figure 8 illustrates this model.



$$M=\frac{W}{2}(l-x)^2 \qquad (1)$$

$$M=\frac{W}{2}(lx-x^2) \qquad (2)$$

Fig. 8: Joint Torque Estimation

Using these rough models and an estimate of a segment's weight of 45.5 kg and length of .610 m, order of magnitude was established for joint torque. Length was taken as 3.6 m and w, weight per unit length, was taken as 731.7 N/m.

Maximum joint torque (quasi static)
cantilever mode 4741 N-m (41,961 in-lbs)
landed mode 1185 N-m (10,490 in lbs)

Note the landed case joint torque is 25% of the cantilevered case. The magnitude of these torques is relatively large. Concepts of joint actuation were considered in light of this requirement.

Radius of turn (for axial center line of the robot) can be used to set segment length and joint range for the robot. A segment with a length of .610 m would require a joint range of ±60 degrees. Some concepts had considerably shorter segment lengths with corresponding smaller joint range requirements.

Many mechanism designs were considered as candidate systems. The selected mechanism is one with two... two degree of freedom parallel planar actuators between joints. The planar actuators are oriented at 90 degrees to each other and are acting on different joints. This configuration gives each segment four degrees of freedom. Two are collinear sliders and two are orthogonal rotations. The two sliding degrees of freedom allow for large changes in segment length. The planar nature of the actuator leads to revolute joint connections. A joint has two orthogonal revolute joints that can intersect (Hooke joint) or have an offset. Joints are connected to each other by two collinear sliders. Figure 9 illustrates this joint configuration.

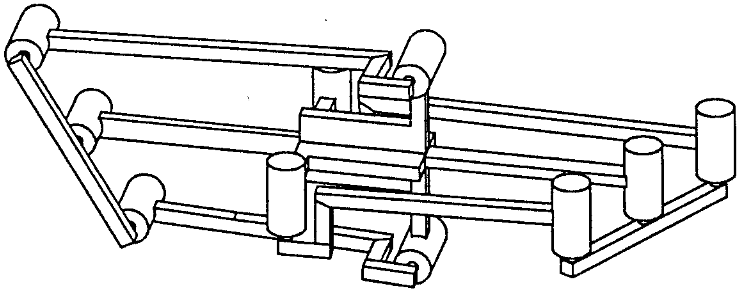


Fig. 9: Orthogonal Parallel planar joint actuation

Parallel actuation gives rise to a distributed mechanism that can be both light weight and rigid. This type of actuation introduces a sliding degree of freedom that improves performance in vertical and bridge navigation.

A working model was designed and fabricated in order to evaluate the suitability of the parallel planar joint actuation scheme with respect to the articulated mobile robot. The first step was to design a segment and the mechanics of a single two degree of freedom actuator. Performance evaluation is being performed for this step. Controllability under load is of prime concern. Secondary is evaluation of the structural integrity of the design.

The mechanical design, fabrication and testing of the apparatus has been performed. A test stand was designed that allowed the body with a two degree of freedom parallel planar actuator to be tested. Loads were applied that duplicate expected loads for a segment of an articulated mobile robot undergoing vertical or bridge navigation. The mechanism meets controllability criteria and load bearing capacity. The mechanical design performed was based on finite element analysis of major components. Design of simpler components was performed using classical methods. The design is centered around currently available linear actuator technology.

Due to cost and availability, servo hydraulics were chosen to power the first segments. The amount of force a hydraulic cylinder under servo positional control can exert is a percentage of the maximum force the cylinder can generate under a given system pressure. The percentage is dictated by stability criteria. A rule of thumb is that optimum power transfer to the load occurs when the pressure applied to the cylinder is equal to 66% of the system pressure [9]. Another consideration in double acting hydraulic cylinders is the different force generating capacity between push and pull strokes. This difference is caused by the reduction of piston surface area by the rod on the pull stroke. A two inch bore cylinder with a 1 3/8 inch diameter rod provides enough force to achieve the required moments. This cylinder has an oversized rod because it has an integral linear transducer. This allows feedback of the cylinder length directly. The cylinder was sized based on the workspace and joint torque requirements.

The basic apparatus designed and fabricated to test the parallel planar actuation concept is illustrated in figure 10. A photograph of the apparatus is shown in figure 11. Each of the mechanical subassemblies are detailed and a brief description is given.

The test stand was fabricated from cold rolled carbon steel shapes. Its principle function is to apply a joint load that can be varied. The loading arm has a sliding weight for applying moments to the actuator. The test

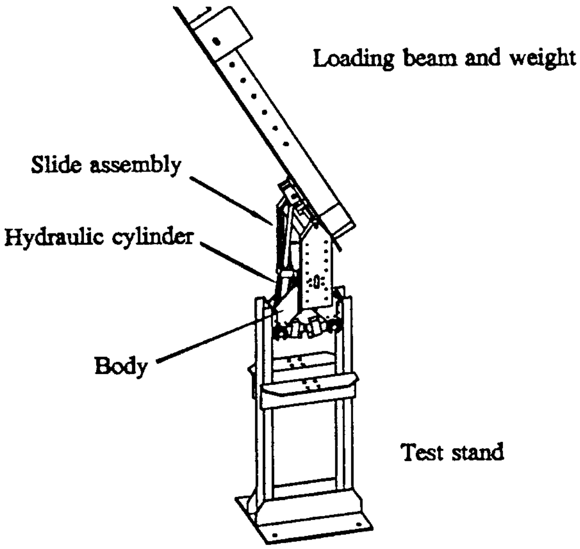


Fig. 10: Apparatus and Test Stand

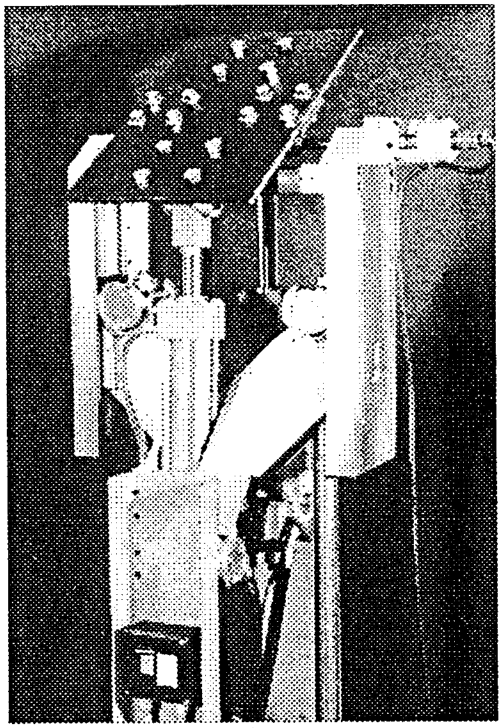


Fig. 11: Apparatus

stand holds the body. The body is illustrated in figure 12.

The material used in the fabrication of the body was 6061 T6 aluminum. The body is a welded assembly. The welding process produced some heat distortion that had to be corrected. The illustration does not show the bearing rings and bearing caps used to fix the trunions of the cylinders in the body. Loads on the body were estimated based on the quasi-static loads on the robot while it is undergoing vertical navigation. A worst case load scenario was deemed to be maximum actuator thrust coupled with a side loading on the order of magnitude of the actuator load. Finite Element Analysis modeling of the body was performed using the estimated worst case loading and approximate geometry. Static deflections and stresses were evaluated using the analysis. A deflection illustration is shown in Figure 13. The deformations are scaled to be approximately 10% of the figure's width. Units are in inches.

The slide assembly is shown in figure 14. It was fabricated from 2024 T351 aluminum. There are two sets of recirculating ball bearing slides mounted in the slide assembly. These slides are induction-hardened ground steel raceways. Recirculating ball bearing blocks are mounted on the caps of the body.

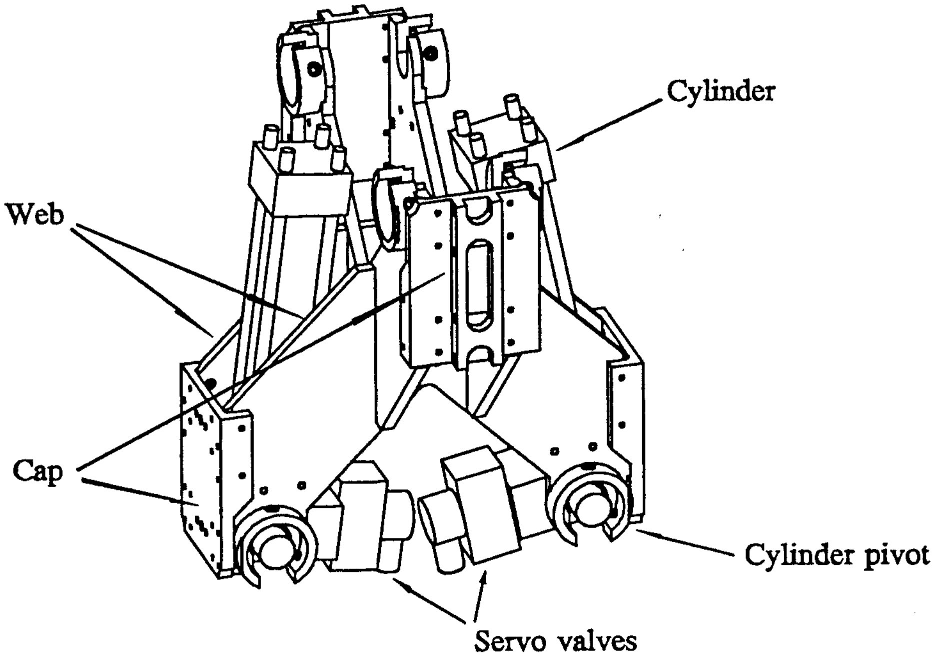


Fig. 12: Body with 1 pair hydraulic cylinders

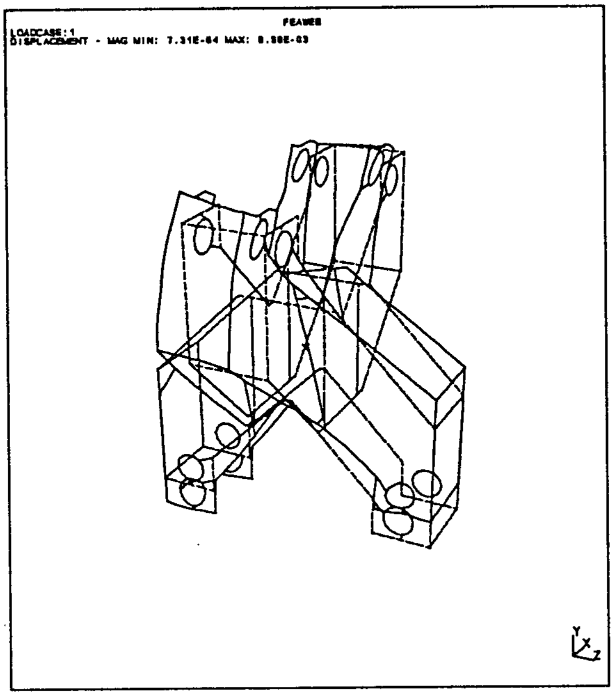


Fig. 13: Deformation of body under expected loading

Two methods of determining the configuration of the parallel planar manipulator exist. One is feedback of actuator length and the other is feedback of the slide length and PPA angle. The test segment has both types of feedback to allow evaluation of each type. Feedback of cylinder length with an integral LVDT results in a cylinder with an oversized rod (reduced pull force). This type of cylinder is also

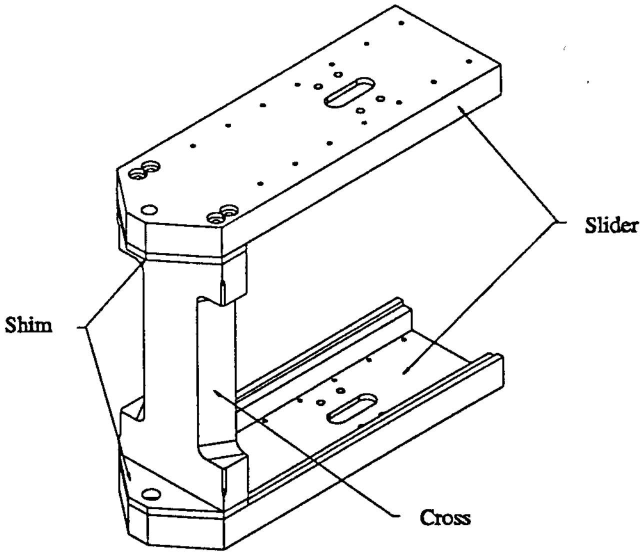


Fig. 14: Slide assembly

heavier that a normal servo hydraulic cylinder (by approximately 25%). Linear displacement is measured by LVDT's in both cases. These are absolute devices with no need of a homing sequence. Angular displacement is measured by an absolute encoder.

The mechanism has been operated under load through it's workspace. No mechanical failure is noted after approximately 100 hours of operation. More extensive evaluations of the mechanism under real-time control are being performed.

5. Conclusion

The three projects described in this paper all deal with the computer control and automation of mechanical systems. All three projects invoke the machine control strategy of plan, execute, and react. Tasks are initially planned, whether they be navigation tasks or commanded actuator motions. The planned task is then decomposed into low level tasks and executed. Finally, sensor data is compiled during the task execution and the machine adjusts its action as necessary.

It has been found throughout these projects that the intelligent machine system must be implemented in hardware. Computer simulations are valuable development tools, but they cannot be relied upon to predict real world conditions and responses. The three projects described in this paper all adhere to this practice. Hardware implementations have been developed to verify the response of all the systems.

6. Acknowledgements

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