A Novel Wire Actuated Parallel Robot with Space Applications

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1. Introduction

Designing robotic systems for space applications requires great attention to light weight, compactness prior to deployment, reliability, failure tolerance and, recently, moderate cost. Traditional serial robots are typically optimized with little regard to the overall weight of the system, rather, weight is redistributed and optimized to minimize the moment produced about joints and to reduce the forces required by motors. For space applications, weight is a critical factor, and must be aggressively minimized. The traditional serial arm requires massive structural components to resist bending loads produced by the arm's weight and payload. In contrast, parallel structures, by virtue of using closed loop geometries, are capable of being designed to support larger loads for a given weight and with greater stiffness.

Conventionally designed parallel robots typically have restricted workspaces relative to their size and weight. This aspect of parallel systems works against their use in space applications. Linear actuators used in some parallel designs are also problematic in a vacuum environment due to the increased difficulty in sealing and preventing lubricant loss. Parallel robots do however have the advantage of high stiffness relative to their weight, offering the potential for design of extremely lightweight systems that can be stowed in compact configurations. This requires that the links comprising the robot be built with high strength and lightweight structure. Designs that carry loads primarily in tension and compression avoid the additional weight and bulk of structural elements carrying loads in bending. Additionally, components loaded only in tension do not need to be capable of withstanding buckling. These requirements and considerations lead to a parallel robot that has only a few solid links to minimize weight, and wire tension members which also serve as actuators.

Previously wire actuators have been used as tendons to actuate serial robots or externally framed wire actuated systems [1]. Earlier work also includes three and six degrees of freedom (DOF) Stewart platform type manipulators actuated by cable tendons [2]. Additionally, substantial work has been done by NIST on the RoboCrane [3], a wire actuated and supported robotic crane, including one variant where a central spine allowed the robot to exert force downwards (which is otherwise impossible in the RoboCrane as gravity keeps the wires taunt).

The approach outlined here uses an articulated central linkage to provide the desired structural stability, DOF and motion. This central mechanism together with winched wire actuation is used to gain a number of important benefits for applications where the advantages of a parallel robot are required in conjunction with light weight.

2. Robot Architecture

The CAT4 (Cable Actuated Truss – 4 DOF) robot under discussion is a four DOF parallel robot utilizing a passively

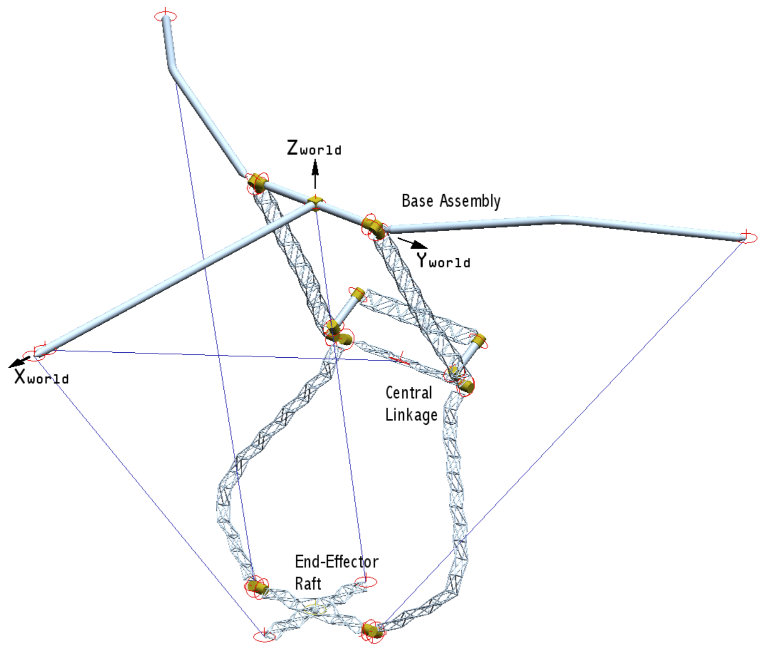

Figure 1: CAT4 robot layout with actual central linkage.

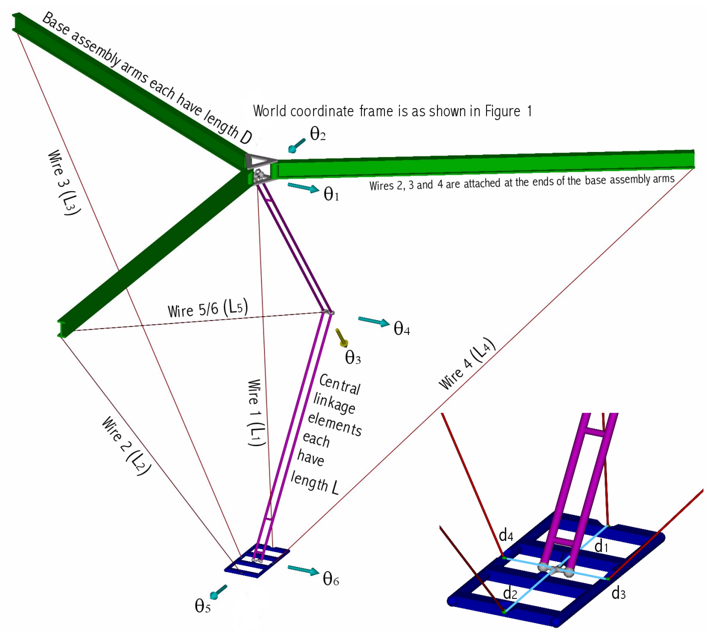

Figure 2: Equivalent constrained serial linkage for CAT4.

jointed central linkage and six control wires for actuation, two of which are used one at a time to solve a robot interference problem. The robot is shown in Figure 1, consisting of a 120° separated Y-shaped structural base assembly at the top, which may be collapsible for transit and forms the backbone of the manipulator. A passive jointed linkage descends from the centre of this structure, with 18 revolute joints. A subset of these joints are sensed by position encoders to allow determination of the end effector position and orientation. This gives the end effector raft attached to this jointed central linkage three translational DOF and one rotational DOF (pitch angle). Brakes are required on the central linkage joints in order to ensure single-string failsafe operation. Six stepper motor actuated winches drive the wire actuators that extend from the top frame to points on the end effector raft and jointed linkage to create a stiff, but lightweight, actuated robot.

This structure can be represented by an equivalent linkage with some constraints applied. The equivalent linkage has a top spherical joint, a revolute elbow joint and a lower universal joint, as shown in Figure 2. The equivalent linkage requires an additional constraint in order for motion to be identical to the actual linkage. This is done by imposing the requirement that the Y axis of the end effector is always kept parallel to the Y axis of the base assembly. These joints provide six DOF, however, the additional constraint reduces this to four DOF, identical to that of the actual linkage.

With reference to Figure 2, the following terms are defined:

- D: Length from world reference frame origin to wire attachment points for wires 2, 3 and 4.
- L: Length of each central link, from the intersection of the top or bottom joint axis to the elbow joint axis.
- P_{EE}: Attachment point of central linkage to end effector raft, at the intersection of the lower universal joint axes.
- d_i: Distance from P_{EE} to attachment point of wire i on the end effector raft, where i=1,...,4, d4=d3
- L_i: Instantaneous actuated wire length, where i=1,...,6

3. Advantages of Proposed System

Parallel robot systems are composed of closed kinematic chains that produce mechanisms with high rigidity. This is due to the non-cantilevered structure of the parallel robot, and is shared by the proposed design discussed here. This rigidity is used to allow the use of lightweight elements as the individual structural links do not have to be particularly stiff to produce satisfactory accuracy.

Non-operating stowed size is an important consideration for robotic systems to be used in space, as compactness is vital to optimize the host or launch vehicle performance. The design discussed here is such that the configuration can be optimized to allow a folded configuration from which the robot can be deployed prior to operation. The stowed volume of this design has not yet been fully analysed but is not expected to be appreciably greater than that of an equivalent serial robot.

Direct kinematics can be problematic with parallel robots, as determining the end effector position from the joint variables can be a difficult problem. The design discussed here however, has a sensed near-serial central linkage, making direct kinematics straightforward.

The overall workspace of the robot is limited in the upper regions by joint limits and the structure of the central mechanism. The robot is best suited to work where the task is generally below the end effector, rather than distributed though the upper portion of the manipulator workspace. This avoids interference with the wires, a problem common to cable actuated parallel robots.

4. Applications

The four DOF parallel robot design under consideration is being examined for its suitability to several tasks related to space exploration. These areas include use as a dextrous grappling device during automated docking of spacecraft and satellites and as a digging arm for soil sampling on other planets or the Moon.

As an aid to spacecraft docking, the use of this design of robotic grapple offers the potential of reducing the necessary accuracy required in guiding the spacecraft together. Once the approach is approximately correct, the grapple device can guide the two spacecraft together, and the compliance within the robot can be designed to absorb the energy of a small velocity difference. For robotic servicing of satellites, and similar on-orbit resupply tasks, this may simplify automated docking. Alternately, once the target has been grappled, it can be manoeuvred within the workspace of the robot arm to facilitate further operations.

As a digging arm, the robot as envisioned is mounted on a lander craft configured such that the frame of the vehicle also forms part of the frame of the robot. The robot is kept folded and stowed in a compact configuration during launch and transit. On deployment, the robot arm would be able to reach a roughly circular ground area from which to obtain samples. The four DOF possessed by the robot allows it to translate in three axes and also to vary the pitch of the sampling tool. This allows the robot to account for variation in surface topography, select an appropriate angle of entry and lift the tool during digging.

5. Kinematic Design and Workspace

A baseline simplified model has been developed. The world reference frame is located with its origin at the intersection of the top spherical joint. The X axis of the frame is in the direction towards the connection point of the base assembly and wires 2 and 5. The Z axis is upwards with the Y axis determined by right hand rule.

For this model of the robot the forward kinematic solution has been determined, however, due to space constraints it is omitted here. Inverse kinematics for wires connected to the end effector raft are straightforward, and can be computed by geometry from the specific layout of the model. Wires connected to the central linkage have more complex inverse kinematics, and at present only a numerical method for evaluation has been found to be tractable.

6. Conclusion

The parallel robot design discussed here is in the process of being more fully developed, and additional details will be presented. In certain applications, it is expected that this design will prove to be competitive with conventional serial robots with regard to weight, stowed volume and robustness.

Future work will include the investigation of velocity, acceleration and force characteristics of the manipulator and development of more refined models for analysis.

7. References

[1] H. A. Akeel: US Patent #5313854, Light Weight Robot Mechanism, May 24, 1994.

[2] S. E. Landsberger and T. B. Sheridan: US Patent #4666362, Parallel Link Manipulators, May 19, 1987.

[3] R. Bostelman, J. Albus, N. Dagalakis and A. Jacoff: “RoboCrane Project: An Advanced Concept for Large Scale Manufactureing”, Proc. AUVSI Conf., paper 407, 1996.