Application of the Trio-Tri-Star Carpal Wrist for use in a Solar Array Tracking Mechanism for the Momentum-eXchange/ Electrodynamic Reboost (MXER) Tether Concept.

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Summary

This paper describes the application of the Trio-Tri-Star Carpal Wrist to the Momentum Exchange Electro-Dynamic Re-boost (MXER) tether, an advanced space transportation concept being developed by the In-Space Propulsion Technology Office at NASA's Marshall Space Flight Center in Huntsville, Alabama. Dr. Joseph Bonometti and Mr. Kirk Sorensen are the principal engineers. In the paper, a brief overview of the MXER concept is given, with an emphasis on the design problem that this wrist is designed to address. The Trio-Tri-Star Carpal Wrist, a three degree of freedom parallel manipulator, invented by Dr. Stephen J. Canfield of Tennessee Tech University, is described with an overview of wrist geometry, kinematics, and stress analysis. A working model of the wrist was assembled at MSFC using Dr. Canfield's prototype to demonstrate its operation. Finally, a design description and supporting analysis of a MXER flight concept wrist is given, with recommendations for future development work.

MXER is an acronym for Momentum eXchange Electrodynamic Reboost. It is a low cost, reusable method that is currently being proposed to boost payloads from low earth orbit to a higher orbit or a lunar trajectory. MXER would be a 60 mile long tether orbiting the earth in a highly elliptical orbit. Distributed along the tether are a series of control nodes that each consists of a reel (like in a fishing rod) and a set of solar arrays extended at the end of a boom. One end of the tether has a catch mechanism which will rendezvous with and capture a payload in a lower orbit and transfer orbital energy from the tether to the payload. Because the tether is in a higher mean orbit and has a greater orbital energy than the payload, the tether is moving much faster than the payload. So to allow the tether to rendezvous with the payload, the tether rotates about its center of mass as it travels along in its orbit, and the tether rotates in a direction that allows the tether tip, at the moment of capture, to match the orbital speed of the payload. The payload is then captured, momentum is exchanged, and the tether slings the payload into a higher orbit while the tether drops into a lower orbit.

To reboost the tether to its original orbit for reuse, an electric current is driven along the length of the tether while it travels through the earth's magnetic field. This sets up an electrodynamic force that adds momentum to the tether and progressively, over the course of thirty to sixty days, nudges the tether back into a higher orbit. The electric current is driven by a potential difference set up between the ends of the tether. The energy for this potential difference is collected from the sun by a set of solar arrays deployed by the nodes. So basically this is a system that harnesses energy from the sun to boost payloads into a higher orbit or a lunar trajectory.

To harness the sun's energy, the tether requires a set of solar arrays to be oriented toward the sun during its tumbling orbit about the earth. Because of the constantly changing position of the sun relative to the solar arrays, a gimbal mechanism is required to keep the solar arrays oriented toward the sun while the control node is rotating. If the solar array is allowed to spin about the pointing axis, a manipulatable universal joint may be used. The Trio-Tri-Star Carpal Wrist was chosen as a unique solution to this design problem. The paper summarizes the design and analysis of a concept wrist intended for the MXER application.

Mechanism Description

The Trio-Tri-Star Carpal Wrist was invented by Dr. Stephen J. Canfield of Tennessee Tech University and its analysis was the subject of his doctoral dissertation at Virginia Tech in 1997. It is a three degree-of-freedom parallel manipulator. It consists of two plates, one fixed, the other free that are connected by three sets of linkages. Each of these linkages consists of two identical links connected to each other by a configuration of revolute joints that allows two degree-of-freedom and the linkages are connected to each plate by a single degree-of-freedom revolute joint on either end. A drive linkage connected to an electric motor actuates each base leg. Figure 1 shows a concept wrist with the components labeled (drive linkages not shown).

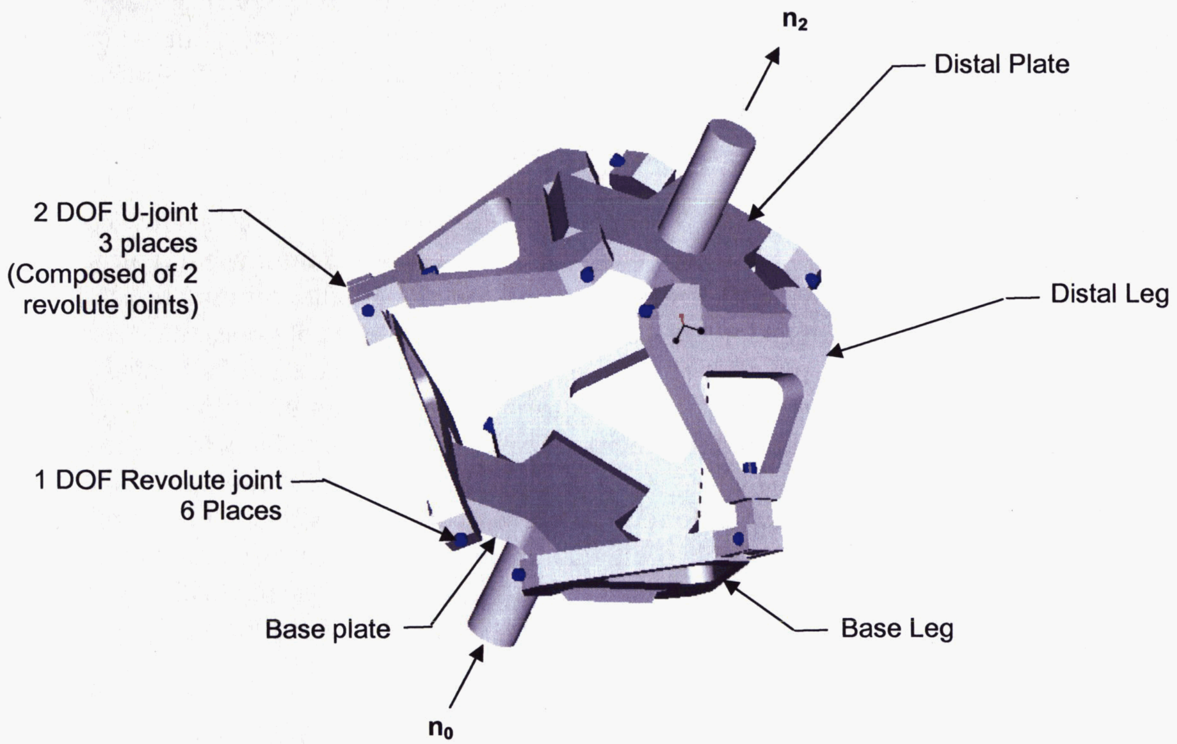

Figure 1. Trio-Tri-Star Carpal Wrist

Analysis

A geometric analysis of the wrist was performed and is described. The geometric analysis was done to determine the relationship between the base leg angles and the direction of the normal to the distal plate. This relationship is important because it allows the wrist to be used to point the solar arrays toward the sun. The geometric analysis is based on the observation that the wrist geometry is symmetric about the plane formed by the ball joint centers. The diagram of this is shown in Figure 2. The results of this analysis are shown in Table 1.

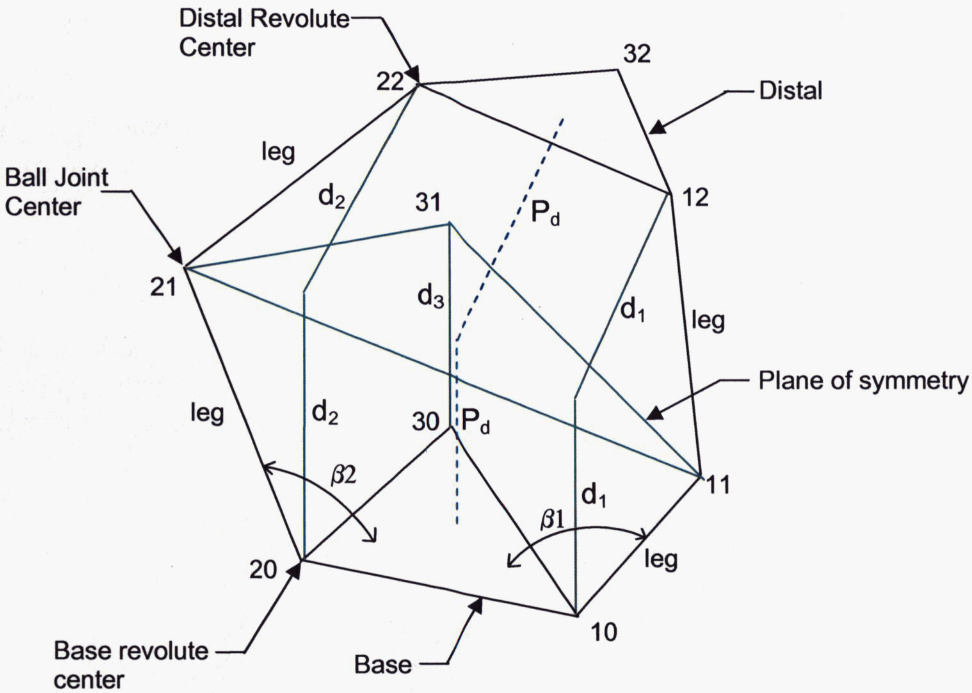

Figure 2. Tri-Tri-Star Carpal Wrist Geometric Diagram

Table 1. Calculated Leg Angles

Base Length:		**3**	**inches**	
Leg Length:		**8**	**inches**	
Plunge Distance:		**5**	**inches**	
Inclination	**Azimuth**	**$\beta 1$**	**$\beta 2$**	**$\beta 3$**
45	**0**	**161.4820**	**141.3178**	**121.3189**
45	**45**	**163.8063**	**124.9508**	**135.3029**
45	**90**	**152.9607**	**118.2813**	**152.9607**
45	**135**	**135.3029**	**124.9508**	**163.8063**
45	**180**	**121.3189**	**141.3179**	**161.4820**
45	**225**	**119.0514**	**157.7832**	**147.3434**
45	**270**	**129.7183**	**164.5989**	**129.7184**

These results were plotted to determine a functional relationship between pointing vector and leg angles. The resulting functions and equations have been determined and are presented in the paper.

Once the geometric relationships of the wrist were mathematically modeled and the leg angles required to achieve the pointing vector were determined, the next step was to determine motion relationships. This allows the development of a control program for tracking of the sun. Functions for the accelerations and velocities of the members were derived and are described in the paper.

An analysis to determine loads was done per a developed procedure and equations to determine maximum loads throughout the working space were developed. The results are presented in the paper.

A preliminary stress analysis of the components was done utilizing the maximum loads. The margins of safety due to static loading and fatigue were determined and are presented in the paper.

Working Model Development

To demonstrate the operation of the Trio-Tri-Star Carpal Wrist, a working model was developed. (see Figure 4). A program utilizing the derived geometric equations was written and validated on the working model. A summary of the working model development activities are provided in the paper.

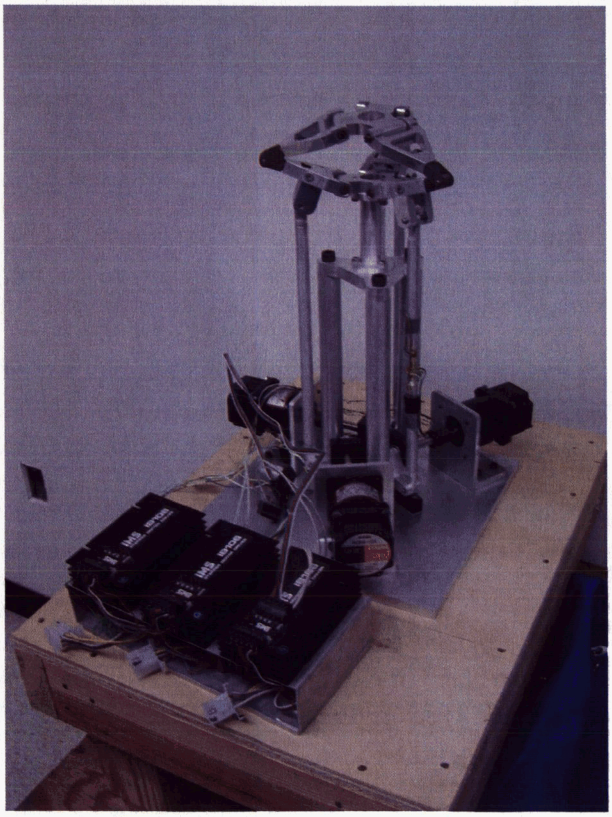

Figure 3. Trio-Tri-Star Carpal Wrist Prototype

Conclusions and Recommendations

The Trio-Tri-Star Carpal Wrist shows promise as an actuated solar array or antenna gimbal mechanism. The geometric analysis of the wrist has been verified in the working model. Further development work will be necessary to validate the loads and stress analysis models. Specific recommendations for future development work are presented in the paper.