Analysis and design of a moment sensitive flexure jointed Stewart Platform based force-torque sensor

M. Prashanth*, Shivanand Bhavikatti*, R. Ranganath[£], and A. Ghosal*
* ME Dept, Indian Institute of Science (IISc) Bangalore 560 012, Karnataka.
[£] Spacecraft Mechanisms Group, ISRO-ISAC, Airport Road, Bangalore- 560017
Email: corresponding author: asitava@mecheng.iisc.ernet.in (A. Ghosal)

Abstract:
This paper deals with the analysis and design of a six-component force-torque sensor. The configuration of the sensor is based on the well-known Stewart Platform manipulator. The key difference between other Stewart Platform based sensors and the one discussed in this paper is the use of a Stewart Platform in a near singular configuration. It is known in kinematics literature that a Stewart Platform at a singular configuration cannot resist some component(s) of externally applied force or moment. At near-singular configurations, a small applied force or moment in certain specific direction(s) can give rise to large forces in the links, resulting in mechanical magnification in link forces. The mechanical amplification enables us to achieve enhanced sensitivity along certain specific directions. This concept is used to design a force-torque sensor which has enhanced sensitivity to the three Cartesian components of externally applied moments. This paper presents the theory to obtain the singular directions of a 6-6 Stewart Platform manipulator, results from finite element analysis of a hinge jointed 6-6 Stewart Platform based sensor sensitive to externally applied moments, and CAD models of the designed sensor.

Keywords: Stewart Platform, singular configurations, force-torque sensor, flexure hinges.

1. Introduction

A force-torque sensor capable of accurate measurement of the three components of externally applied force and moment is required for force control in robotic assembly operations. A six-component force-torque sensor is also useful in aerospace applications such as in the measurement of contact forces and moments in space docking and measurement of lift, drag and other quantities in a wind tunnel. To satisfy these needs, a large amount of literature exists on the design of force-torque sensor (Gorinevsky et al[1]). The original proposal of using a Stewart Platform for a flight simulator by Stewart [2] has been followed by its use in a variety of applications including a six component force-torque sensor. This is due to its inherent advantages of being a parallel device (see, for example, Gaillet and Reboulet[3], Dwarakanath et al.[4] and the references in them).

It is observed from an extensive literature survey that the use of a Stewart Platform as a six component force-torque sensor is aimed towards an isotropic configuration to achieve approximately equal sensitivity for all components of the applied external force-torque. The goal in this paper is to design a Stewart Platform based force-torque sensor at a near-singular configuration sensitive to externally applied moments. In such a configuration, as we show in this paper, we obtain enhanced mechanical amplification of leg forces and thereby higher sensitivity for the applied external torque. In other directions, the sensitivity will be that of a normal load sensor determined by the sensitivity of the sensing element and the associated electronic amplification, and we can sense all the six components of the force and torque. The idea of a near-singular configuration was first used by Ranganath et. al [5] to design and develop a force-torque sensor with enhanced sensitivity to forces in the horizontal plane and moment about the vertical direction. In this paper, we present a force-torque sensor which is sensitive to the three components of the externally applied moment. This paper is organized as follows: in Section 2, we present a general method to obtain the singular directions of a 6-6 Stewart Platform. In Section 3, we present the design procedure followed by us to meet the specifications of a force-torque sensor. In this section we also present finite element analysis (FEA) results and the CAD models of the designed sensor. Section 4 presents the conclusion and the plan of future work.

2. Singular directions of a 6-6 Stewart Platform

The Stewart Platform, as shown by a line diagram in Figure 1, consists of six extensible legs (with prismatic joints in each leg) connected to the (moving) top platform and (fixed) base with spherical(S) joint and Hook(U) joints respectively. As a manipulator, the Stewart Platform has six degrees-of-freedom - by actuating the six legs, arbitrary position and orientation of the moving platform can be achieved. If an external force-moment is applied at the top platform, we can obtain the axial forces in the legs required to keep the Stewart Platform in equilibrium (see, for example, Dasgupta [7] for details).

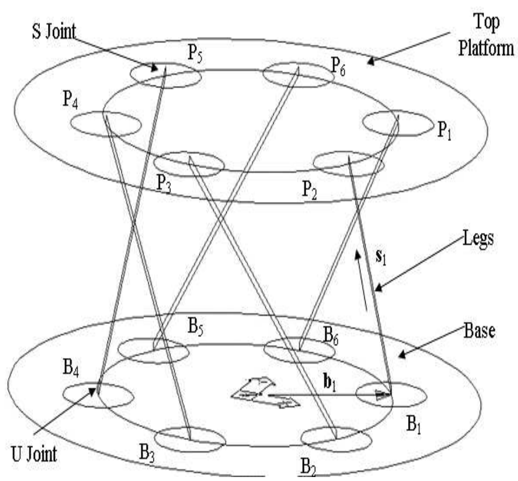

Fig 1 – Line diagram of a 6-6 Stewart platform based sensor

The relationship between the six leg forces and the external applied force **F** and moment **M** is given by the matrix equation

$$(\mathbf{F};\mathbf{M})^T=[H]\,\mathbf{f} \qquad (1)$$

where the matrix 6 x 6 matrix [H] is made up of the unit vectors along the legs and the moment of these unit vectors from the origin of the fixed coordinate system located at the centre of the fixed platform. Denoting the leg unit vectors by $\mathbf{s}_i$, i=1,...,6 and the moments by $\mathbf{b}_i \times \mathbf{s}_i$, i=1,...,6, the [H] matrix is given as

$$[H]= [(\mathbf{s}_1;\, \mathbf{b}_1 \times \mathbf{s}_1)^T \mid ....|(\mathbf{s}_6;\, \mathbf{b}_6 \times \mathbf{s}_6)^T\,] \qquad (2)$$

where i^{th} column of [H] is the 6 x 1 entity $(\mathbf{s}_i;\, \mathbf{b}_i \times \mathbf{s}_i)^T$.

The matrix [H] is called the force transformation matrix and maps leg forces to externally applied force and moment. If the matrix [H] is singular, some component(s) of the externally applied **F** and **M** cannot be supported by the structure of the Stewart Platform obtained by locking the prismatic joints. The structure in such a case gains one or more degrees of freedom instantaneously. The eigenvectors corresponding to the zero eigenvalues of [H] when mapped to 3D space give the singular directions, and the Stewart Platform cannot withstand any force/moment applied along the singular directions. If the Stewart Platform is in a near-singular configuration, then a small non-zero force/moment acting along the singular direction will lead to large axial force in one or more of the legs, and we will get large magnification. This key concept is exploited in the design of the force-torque sensor in this paper.

From equation (1) and (2), the external force, **F**, can be written as

$$\mathbf{F}=[H_f]\,\mathbf{f} = (\,\mathbf{s}_1 \mid \mathbf{s}_2 | ...|\, \mathbf{s}_6)\,\mathbf{f} \qquad (3)$$

The square of the magnitude of **F** is given by

$$\mathbf{F}^T\mathbf{F}= \mathbf{f}^T [g_f]\;\mathbf{f} \qquad (4)$$

and the maximum, intermediate and minimum values of $\mathbf{F}^T\mathbf{F}$ subject to a constraint of the form $\mathbf{f}^T\mathbf{f}=1$ are the eigenvalues of $[g_f]$. Since the rank of $[g_f]$ is 3 ($[H_f]$ has at most rank 3), we can show that the tip of the force vector, **F** lies on an ellipsoid in 3D space. The axes of the ellipsoid are along the *principal forces* and these can be obtained by mapping the eigenvectors corresponding to the non-zero eigenvalues of $[g_f]$ by [H].

Since $[g_f]$ has maximum rank 3, three eigenvalues are always zero and the eigenvectors corresponding to these zero eigenvalues when mapped by [H] give the *principal moments* at the origin. If the rank of $[g_f]$ is less than three, the force ellipsoid shrinks to an ellipse, a line or a point. The singular directions of force can be obtained by mapping the eigenvectors corresponding to the extra zero eigenvalues of $[g_f]$. Likewise the singular direction of the moments is the null space of the matrix obtained from the principal moments.

Using the above procedure, we investigated several 6-6 Stewart Platform configurations, with equal sized hexagonal base and platform (the details are available in Ranganath.[8]), by changing the connection sequence between the base and platform points. It was observed that the connection sequence **B_1-P_2, B_2-P_3, B_3-P_4, B_4-P_5, B_5-P_6, B_6-P_1** had singular directions along the three components of the externally applied moment **M**. Hence, a Stewart platform in near singular configuration with the legs skewed and having a connection sequence **B_1-P_2, B_2-P_3, B_3-P_4, B_4-P_5, B_5-P_6, B_6-P_1** will posses enhanced sensitivity to M_x, M_y, and M_z. This configuration was chosen for future analysis and design and is shown as a line diagram in Figure 1.

3. Design Procedure

In this section, we present the design procedure followed by us to design the six component force-torque sensor. We start with the design specifications provided to us by ISRO.

3.1 Specifications

Table 1 – Specifications of force-torque sensor

Size of sensor
Diameter =80.0 mm Height = 42.0 mm Thickness of base platform = 5.0 mm Diameter of leg = 12.0 mm
Load Specification
Force along roll axis: Fz (out of plane) = 200 N & sensitivity = 0.5 N
Force along pitch axis: Fx (in-plane) = 50 N & sensitivity = 0.25 N
Force along yaw axis: Fy (in-plane) = 50 N & sensitivity = 0.25 N
Moment about roll axis: Mz = 10000 N-mm & sensitivity = 50 N-mm
Moment about pitch axis: Mx =10000 N-mm & sensitivity = 50 N-mm
Moment about yaw axis: My = 10000 N-mm & sensitivity = 50 N-mm
Materials used
Base & platform – Aluminum alloy: E= 69356.7 N/mm^2; G = 26675.65 N/mm^2 & Poisson's ratio υ = 0.3
Legs & rings – Titanium (Ti-6Al-4V) alloy: E = 109872 N/mm^2, G = 42258.46N/mm^2 & Poisson's ratio υ = 0.3

The force-torque sensor is to be fixed to a robot being developed by ISRO. Due to this requirement certain specifications on geometry and size were given by ISRO. The specifications on the size of the sensor are shown in Table 1. In addition, the sensor is required to mounted between the robot wrist and the payload, and for this a set of holes with PCD 58mm is required on the top platform. It was also specified that there should be no interference of any part of the sensor with these holes. The load specification was also specified by ISRO and these are given in Table 1.

3.2 Choice of Configuration

As mentioned in Section 2, we have chosen a Stewart Platform in a near singular configuration. The leg connection sequence was chosen as **B_1-P_2, B_2-P_3, B_3-P_4, B_4-P_5, B_5-P_6, B_6-P_1.** We performed extensive numerical simulations in Matlab to obtain a near singular configuration. Eventually we decided on a 30-33 angle combination where 30 degrees is the half angle between the two base points and 33 degrees is the half angle between the two platform points. To make the top platform a regular hexagon the alternate angles are 33 and 27 degrees in the top platform. The choice of 30-33 angle combinations make the legs of the Stewart Platform tilted in two planes. Once the angle combination is chosen, the nominal coordinates of the top and bottom connection points can be obtained from the size specifications given by ISRO. These are given in Table 2.

Table 2: Co-ordinates of Base and Top Platform connection points (in mm)

BASE	X	Y	Z
B_1	21.65	12.5	0
B_2	21.65	-12.5	0
B_3	0	-25.0	0
B_4	-21.65	-12.5	0
B_5	-21.65	12.5	0
B_6	0	25.0	0

TOP	X	Y	Z
P_1	22.27	11.35	37
P_2	22.27	-11.35	37
P_3	-1.31	-24.97	37
P_4	-20.97	-13.62	37
P_5	-20.97	13.62	37
P_6	-1.31	24.97	37

For the chosen angle combination and the coordinates of the connection points in the top and bottom platform, the condition number of the [H] matrix is found to be 707 – the condition number is not too high and it was observed that we get a fairly good magnification. For example, for the smallest applied force of (0.25, 0.25, 0.50) N and the applied moment of (50, 50, 50) N-mm, the six leg forces, as obtained from Matlab simulations, are given in the last column of bottom half of Table 3. One can observe that the leg forces are reasonably large even for the smallest applied load. Table 3 also gives the leg forces for the largest applied load.

Table 3: MATLAB results showing Leg forces in each leg for Force and Moments

MATLAB RESULTS							
LEG FORCES (Maximum Force)							
	Fx= 50	Fy= 50	Fz= 200	Mx= 10000	My= 10000	Mz= 10000	Fx, Fy, Fz, Mx,My, Mz
F1	282	-553	1302	3254	-1994	-6208	-3918
F2	-635	-33	-1254	-3042	-1864	6355	-473
F3	338	521	1302	100	3815	-6208	-133
F4	346	-533	-1254	3135	-1702	6355	6347
F5	-620	32	1302	-3354	-1821	-6208	-10669
F6	289	566	-1254	-93	3566	6355	9428
LEG FORCES (Minimum Force)							
	Fx=0 .25	Fy=0 .25	Fz=0 .50	Mx=5 0	My=50	Mz=5 0	Fx,Fy,F z, Mx,My, Mz
F1	1.4	-2.8	3.3	16.3	-10.0	-31.0	-22.8
F2	-3.2	-0.2	-3.1	-15.2	-9.3	31.8	0.8
F3	1.7	2.6	3.3	0.5	19.1	-31.0	-3.9
F4	1.7	-2.7	-3.1	15.7	-8.5	31.8	34.9
F5	-3.1	0.2	3.3	-16.8	-9.1	-31.0	-56.6
F6	1.4	2.8	-3.1	-0.5	17.8	31.8	50.3

We also made a finite element model of the six component force-torque sensor. To verify the model we used the end release option (to simulate spherical joints) and applied the smallest and the largest loads. The results obtained from NISA package was in full agreement with the Matlab results shown in Table 3.

3.3 Choice of flexible joints in legs

The Stewart Platform in its original form has Hook (U) and Spherical(S) joints. In a sensor application, motion at the joints introduces nonlinear effect such as friction, backlash and hysterisis. To avoid these nonlinear effects we use flexible joints. Figure 2 shows two kinds of flexible joints analysed in literature (Ranganath et al.[5], Paros and Weisboard[6]). In our case, we attempted to use the flexible joints shown in figure 2. However, it was observed that the largest specified loading was too large and the joints would fail. Instead of the joints in figure 2, we have used joints as shown in figure 3. The main difference between the flexural joint in figure3 is that to accommodate rotations about two perpendicular axis, we have placed the thin sections at two different locations perpendicular to each other. It was found during simulations that the joint shown in figure 3 is much stronger than the ones in figure 2.

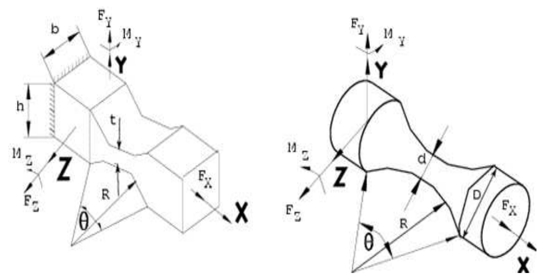

Fig 2 – Flexure joints

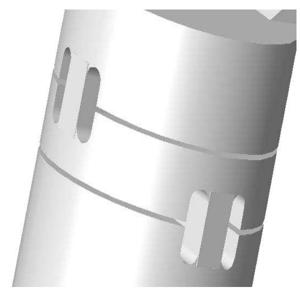

Fig 3 – Flexural hinge used in design

The flexural hinge was modeled in NISA (together with the rest of the sensor) and we performed extensive NISA simulations. The goal was to obtain a design which would not fail for the largest loading and which would satisfy the height specifications. The key dimensions of the flexural hinge, shown in figure 3, are given below.

<u>Leg diameter</u> = 12.0 mm

<u>Two-axis flexure</u> Length = 3.0 mm,
Thickness = 1.5 mm

3.4 Design of sensing element

In a Stewart Platform based force-torque sensor the prismatic joint is replaced by a sensing element. Our goal is to measure the axial leg force which can be positive or negative. A commonly used approach is to use a proving ring with strain gauges attached to the mid-section of the proving ring. The dimensions of the ring, namely inner and outer diameter, thickness and face width determines the strain at the mid-section. The design of the ring sensing element should be based on the smallest load – the dimensions should be such that the smallest loading gives at least a measurable strain reading. The design is also based on the largest loading, namely it should not fail for the largest loading. After extensive simulation using NISA, we arrived at the following dimensions for the ring sensing element shown in figure 4.

Ring geometry

Outer dia = 17.25 mm, inner dia = 14.75 mm
Thickness = 1.25 mm, Face Width = 4.0 mm

For this geometry, the strain value for the smallest loading was obtained as 1.3 micro-strains. Since we will be using four strain gauges in each sensing element, the smallest strain reading would be 5.2 micro-strains and this can be easily measured by conventional electronics.

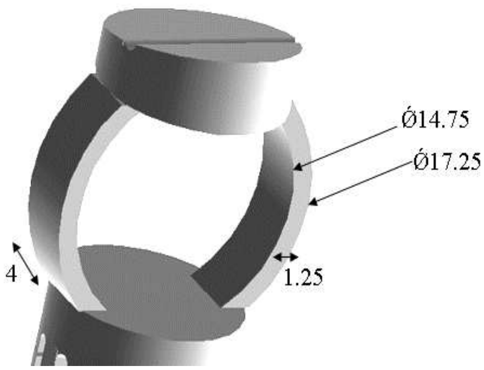

Fig 4 – Ring sensing element

3.5 FE modeling and analysis of the sensor

With the leg and ring dimensions finalized, we chose the top and bottom plate to be of 5mm. The full sensor was modeled in NISA and the details of the NISA model are given below.

Finite element details of the sensor

1) The finite element model has totally about 48400 degrees of freedom
2) B.C to the base points at which the sensor is fixed to the ground are assigned zero displacement (Ux = Uy = Uz = 0) & zero rotation boundary conditions (Rx = Ry = Rz = 0).
3) The top & bottom end of the legs are node merged to the platform & base respectively.

Table 4 below shows the type of elements used to model respective members of the sensor in NISA

Table 4 Elements used to model the Sensor in NISA

Member	Type of element used
Base, platform & ring	Shell elements (NKTP = 20)
Leg	Beam elements (NKTP = 12)

The FEA model was simulated and we present some of the results. Table 5 shows the values strain in each leg for the largest and smallest load. As mentioned earlier, for the smallest load the smallest strain is 1.31 micro-strains. Since four strain gauges will be used this value can be easily measured. The strain values for the largest load are quite large and we can easily measure them with standard strain gauges and electronics.

Table 5 – FEM Analysis results

	Strain Values in each Leg					
	Leg1	Leg2	Leg3	Leg4	Leg5	Leg6
Maximum Load	1401	3022	2746	407	1487	557
Minimum Load	6.19	14.38	12.91	1.31	8.25	5.82

Figure 5 and 6 show the Von-Mises stresses and the deflection of the sensors for the largest loading. The maximum stress developed due to the maximum applied load, as given in Table 1, is 465.4 N/mm^2. This shows that the design is safe since the Titanium (Ti-6Al-4V) alloy yields at a stress of 880 N/mm^2 and we get a factor of safety of about 2.0.

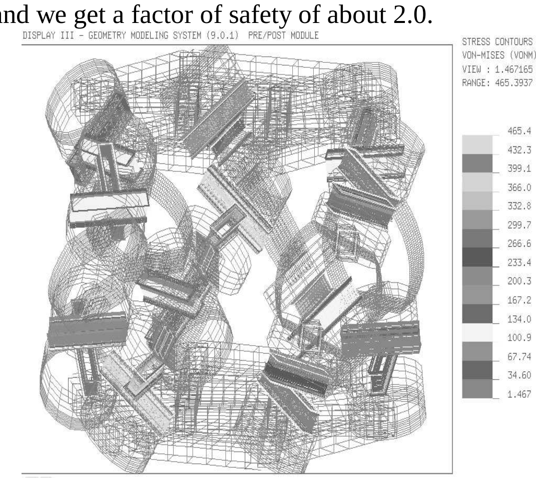

Fig 5 Stress Contours-Von-Mises Stress in NISA

The displacement in the model for largest loading is shown in figure 6. The maximum linear displacement observed in NISA model is 0.6154 mm

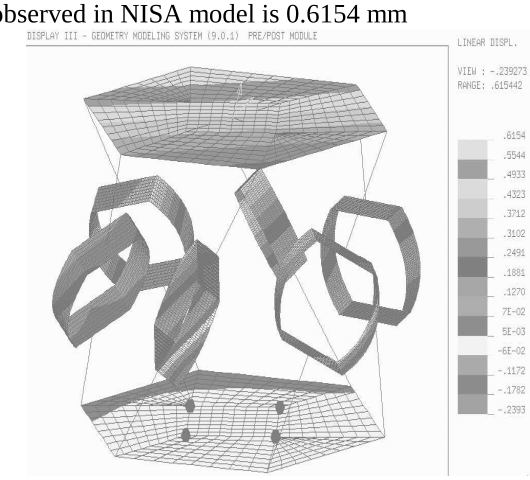

Fig 6 Linear Displacement in Ring and Plate in NISA

3.6 CAD models

The designed force-torque sensor was modeled in UniGraphics and the manufacturing drawings have been made in AutoCAD. We show only the CAD models in this paper.

Due to the chosen 30-33 angles and the chosen configuration, there are two kinds of legs. The two legs are shown in Figure 7. The first model in figure 7 shows a leg without consideration of how the legs must be attached to the platform. We plan to attach the legs with two ears like ends. The ears surface mating with the platform must be flat. To make manufacturing easy we have designed the ears such that they can be cut in a single operation. The two kinds of legs with two different ear geometries are also shown in figure 7. The ears have two tapped holes and the platform can be attached at these two holes by screws. A central hole of diameter 20mm is provided in the top and bottom plates for electrical wire connection.

The full CAD model of the sensor is shown in fig 8.

Fig 7 – CAD model of legs

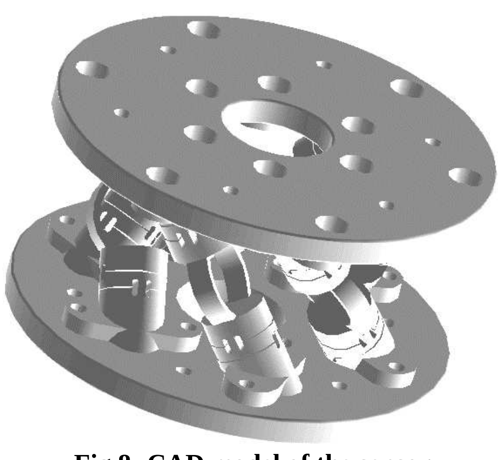

Fig 8- CAD model of the sensor

4. Conclusions

In this paper, we have described the analysis and design of a Stewart Platform based six axis force-torque sensor. From the given specification, we first chose a configuration which had enhanced sensitivity for the externally applied moment components. The initially chosen configuration was perturbed to obtain a near-singular configuration and extensive numerical simulations were performed using Matlab to demonstrate the feasibility of the chosen configuration. For the actual sensor, the kinematic joints were replaced by flexural hinges and the ring shaped strain sensing element was introduced. Extensive FEA simulations in NISA were carried out on the structure to ensure that the designed sensor met the required specifications. A CAD model of the sensor has been prepared and the sensor is in the process of being fabricated. Once the sensor is fabricated, we will perform testing and validation.

References:

1. Gorinevsky, D. M., Formalsky, A. M., and Schneider, A. Y., Force Control of Robotics Systems, CRC Press, New York, 1997.
2. Stewart, D., A platform with six degrees of freedom, Proc. of Institution of Mechanical Engineers, Part 1, Vol. 180(15), 1965, pp. 371-386.
3. Gaillet, A. and Reboulet, C., A isostatic six component force and torque sensor, Proc. of the 13 Int. Conf. on Industrial Robotics, 1983, pp. 18.102-18.111.
4. Dwarakanath, T. A., Dasgupta, B. and Mruthyunjaya, T. S., Design and development of a Stewart Platform based force-torque sensor, Mechatronics, Vol. 11, 2001, pp. 793-809.
5. Ranganath, R., Nair, P. S., Mruthyunjaya, T. S., and Ghosal, A., "A force-torque sensor based on a Stewart Platform in a near-singular configuration", Mechanism and Machine Theory**,** Vol. 39, pp. 971-998, Sept., 2004 **.**
6. Paros, J. M. and Weisbord, L., How to design flexure hinges, Machine Design, 1965, pp. 151-156.
7. Dasgupta, B., The Stewart Platform Manipulator: Dynamic Formulation, Singularity Avoidance and Redundancy, Ph.D. thesis, IISc, 1996.
8. Ranganath, R., Analysis and design of a Near-Singular Stewart platform Based Force-torque Sensor, Ph.D. thesis, IISc, 2002