Methodology to Determine Counterweights for Passive Balancing of a 3-R Orientation Sensing Mechanism using Hanging Method

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Abstract

Orientation control of an object is an important aspect of robotics. Modern day controllers should not only be versatile but should also be energy efficient and the concept upon which the device works should be easy to understand by the user, i.e., it should be intuitive. A novel serial chain mechanism to measure orientation, 3-R Orientation Sensing Mechanism (3-ROSM), was proposed elsewhere, which consisted of 3-Revolute joints that intersect at the center of the user held end-effector. The mechanism had extensions in two links to place counterweights in orthogonal directions to a joint axis, for passive balancing. In this paper, the methodology to determine the location of the counterweights on the physical prototype of the mechanism is proposed. Thereafter, using the proposed methodology, a physical prototype of the orientation sensing mechanism has been developed that has passive balancing capabilities.

Keywords: passive balancing, orientation sensing mechanism, counterweight balancing, hanging method

1 Introduction

In the field of robotics, several instances exist when the orientation of an object has to be controlled using input devices. Orientation sensing mechanisms are capable of sensing the change in orientation of an object, which can be achieved with or without the help of electronics. The benefits of using a purely mechanical device are that it's more cost effective and energy efficient. These mechanisms can be broadly classified into parallel and serial mechanisms. Low inertia, compactness, high rigidity, and precise resolution are characteristic of parallel mechanisms. For example, SHaDe [1] is a 3-DOF (degree-of-freedom) mechanism consisting of parallel linkages which can be used in applications involving control of orientation, but has a restricted range of motion. In [2], a design of a 6-DOF haptic parallel mechanism, utilizing three ground servomotors to drive three pantograph mechanisms, was used to interface with virtual reality applications. However, the kinematics of parallel mechanisms is complicated as compared to that of serial mechanisms. This type of mechanism, commonly seen in joysticks or controllers such as the Geomagic Touch (formerly known as Phantom Omni), has a much simpler architecture and a wide workspace, but a lower resolution of joint angle measurement as compared to a parallel mechanism. The 3-ROSM is a serial mechanism with three intersecting axes, which aims to have a wide workspace with better resolution than conventional serial mechanism.

In pure mechanical hand held mechanisms such as the 3-ROSM, additional balancing techniques are required such that the configuration of the mechanism remains unchanged even after the user ceases to hold or use it. Active and passive balancing are the two types of balancing that can be implemented in such systems. Active balancing uses external actuators such as motors, hydraulic or pneumatic means to continuously stabilize the system. As shown in [3] which pumps fluid continuously from one reservoir (which acts as a counterweight) to another in to adaptively balance a system in which the mass is not constant. Passive balancing includes the use springs or counterweights to compensate the action of gravity on the links of the system. This type of balancing using counterweights is used in the 3-ROSM making it a Hand operated Balanced Mechanism [4].

In this paper the modifications done on the 3-ROSM are reported along with a methodology (proposed elsewhere) to determine practically the Centre of Gravity of different links on the mechanism, which in turn will determine accurate counterweight placement to achieve passive balance. Also to increase the adaptability of the system to changes in mass, the counterweights run along a thread which allows the user to balance variable loads in the system.

2 The 3-ROSM Concept

The novel serial chain mechanism called the 3-Revolute Orientation Sensing Mechanism, proposed in [5] has three moving links (Link1, Link2, and Link3) and a fixed link (Link0) connected in series as shown in Figure 1. The mechanism is passively balanced about joints Joint1, Joint2 and Joint3, and the joint axes intersect in a user held End-effector (EE) mounted on Link3. The intersection of axes emulates the wrist of a 6-axis wrist partitioned robot, which helps the user attain a more intuitive control of an object. The spherical shaped object on the EE can be held by the user to change the configuration of the mechanism. Hence, as the user moves the EE, the center of the sphere remains at the same position and only its orientation changes with respect to the fixed link. In [5] the architecture of the mechanism has been represented using DH parameters to prove the usability of the 3-ROSM as an orientation sensing mechanism.

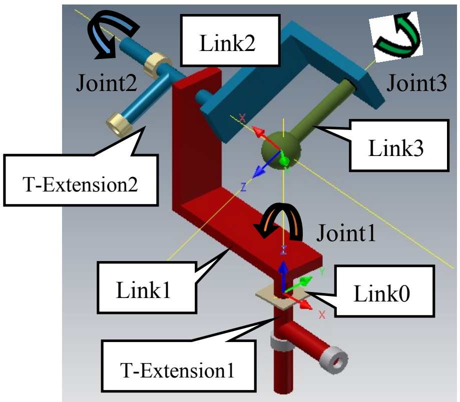

Figure 1: CAD Model of the 3-ROSM

In the initial design of the mechanism, passive gravity compensation using counterweights prevents the reorientation of the links due to the action of gravity. To facilitate placement of the counterweights in 2-dimensions, T-shaped extensions were attached to the initial system of the 3-ROSM as shown in Figure 1. This novelty allowed for the reduction of a 3-dimension balancing problem into two sets of 2-dimension balancing problems, hence reducing the complexity of achieving passive balance of the system.

2.1 Method to find mass centers in CAD software

In [5], the passive balancing of the 3-ROSM was achieved using the appropriate placement of predetermined counterweights on the T-extensions. The locations of the counterweights were found using the moment balancing equation about corresponding joint axes. The balancing of the entire 3-ROSM is split into initial balancing of Link2 and Link3, which accounts for the gravitational force acting vertically downwards and the balancing of all the links of the 3-ROSM ensures that the configuration of the links remains unchanged for any component of gravitational force acting on it. In Figure 2, the locations of the Centers of Gravity of the individual links are shown for balancing along axis of Joint2.

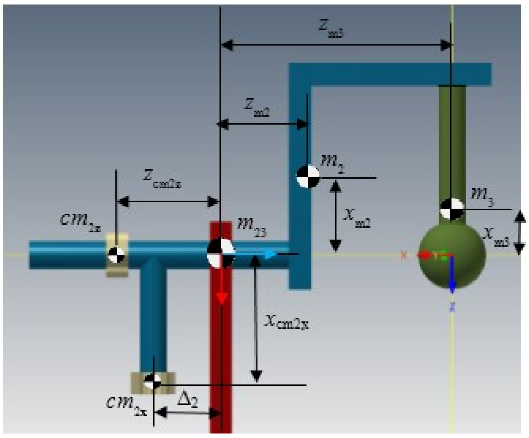

Figure 2: Balancing of the Links of the 3-ROSM about their respective joint axes

These values along with the mass taken at uniform density are placed in moment balancing equations below to find the locations at which the counterweights should be placed in order to achieve static balance.

$$(m_2 \cdot x_{m2}) + (m_3 \cdot x_{m3}) = (cm_{2x} \cdot x_{Cm2x}) \quad (1)$$

$$(m_2 \cdot z_{m2}) + (m_3 \cdot z_{m3}) = (cm_{2z} \cdot z_{Cm2z}) + (cm_{2x} \cdot \Delta_2) \quad (2)$$

The theoretical locations of the counterweights were calculated and counterweights were placed in Autodesk Inventor CAD software. Using the Dynamic Simulation module of this software, the assembly was subjected to gravity force and it was observed that proposed passive balancing technique works as expected.

2.2 Improvements proposed in the 3-ROSM

One of the objectives of this paper is to increase the adaptability of the 3-ROSM. To ensure that the mechanism can be used in a variety of applications, the user should be able to apply changes to the system as and when required, e.g., the addition of sensors to measure the changes in joint angles. Also, the masses of the links and counterweights in the initial design of the 3-ROSM were definite and did not account for mass irregularities, which is observed when approaching a practical design of the mechanism such as the addition of wires or non-uniformity of the link mass.

To account for such mass changes, which the authors believe would affect the overall passive balance of the system, the T-extension are threaded externally and the counterweights are threaded internally. Therefore, if there is any change in mass of the system, the counterweights can be moved, finely, along the T-extension to a new calculated location. Hence, the thread allows for infinite resolution for the accommodation of the counterweights.

3 Physical Prototype

The objectives of developing a physical prototype of the 3-ROSM are to test its usability as an orientation sensing mechanism, to validate counterweight balancing techniques utilized by the mechanism and to apply the above stated improvements to increase the overall adaptability of the 3-ROSM. The key areas of focus during the construction of the prototype are to maintain low joint friction as when the joint angles are measured, high friction would cause backlash. Also, the low values of moment acting on the mechanism are heavily influenced by friction and may affect the validation of the counterweight balancing techniques used. The Links of the 3-ROSM were made of 10mm thick acrylic sheet, which were laser cut to accurate dimensions obtained from a CAD model of the mechanism. Acrylic has good rigidity, is easy to work with and relatively less expensive as compared to a full metal model. Assembled mechanism is shown in Figure 3.

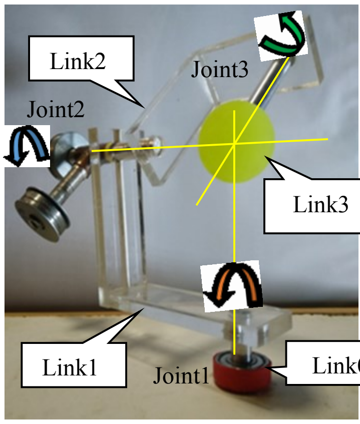

Figure 3: Physical Prototype of the 3-ROSM

The shafts joining the entire mechanism were made of smooth aluminum rods which are light weight, allowing for the majority of the weight to be distributed on the links.

The smoothness ensures reduced friction during joint rotation. The rods used in the T-extension were then threaded to a specification of M12 with a 1.75 pitch. A ball bearing was used at Joint1 as the load at this joint is comparatively higher and the mass of the bearing does not contribute to the balancing of the mechanism. Therefore, a different approach was taken at Joint2 as a bearing cannot be used here. the vertical portion of Link1 was split into two and rejoined over Joint2 which had a smaller diameter than the rest of the shaft. This eliminated translation motion about any other axis. The same procedure is applied to Joint3 but the addition of grub screws was necessary to keep Link3 in place and to prevent it from falling due to gravity. It must be noted that there may be non-uniformity in mass distribution of the links due to manufacturing defects and the complexity in the shape of the thread makes it difficult to get accurate counterweight locations from the moment balancing equations.

3.1 Determination of location of counterweights

To place the counterweights accurately in the prototype of the 3-ROSM, the location of the Center of Gravity (CG) of each link must be known. The CG of the links, which are a combination of primitive shapes, can be found theoretically using the size and density of the material. However, it could have some inaccuracies as the defects mentioned in the previous section could arise. Hence, a method used in [6] referred to as the Hanging Method was used to find the practical CG of each link.

The Hanging method is a commonly known method which involves hanging the link in consideration by different points from a fixture. A vertical plumb line is then dropped from the same fixture. As the CG of the link always lies below the point of suspension, the intersection of two plumb lines for different orientation of the link is taken as the effective CG of the link. A third plumb line may be dropped as a means of verification of the point of intersection. The procedure is illustrated in Figure 4.

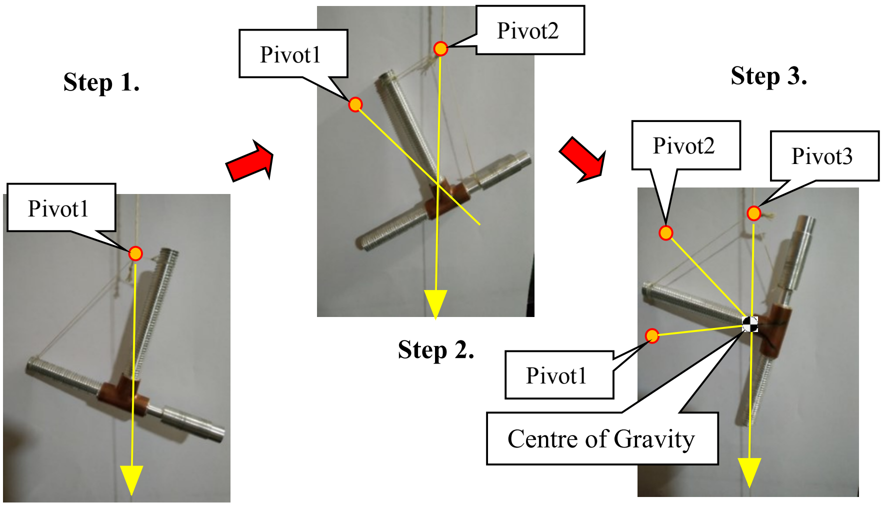

Figure 4: Hanging Method applied on a T-Extension of the 3-ROSM

In the case of the T-extension, the CG is located on the object as shown in the figure. In other cases, when the CG is located off the object, a massless sheet is attached to the link and due to the symmetry of the link the CG can be plotted on the sheet. The locations of the Centers of Gravity are plotted using the plane of symmetry of the objects as a Cartesian plane with the origins centered at Joint2 (in the balancing of Link2 and Link3) and at Joint1 (in the balancing of the entire mechanism)

3.2 Experimental values

The CG locations obtained by the Theoretical Method and the Hanging Method for the links about Joint 2 axis (shown in Figure 5) are compared in Table 1. The authors believe that the small variation in values can affect the overall balancing of the mechanism.

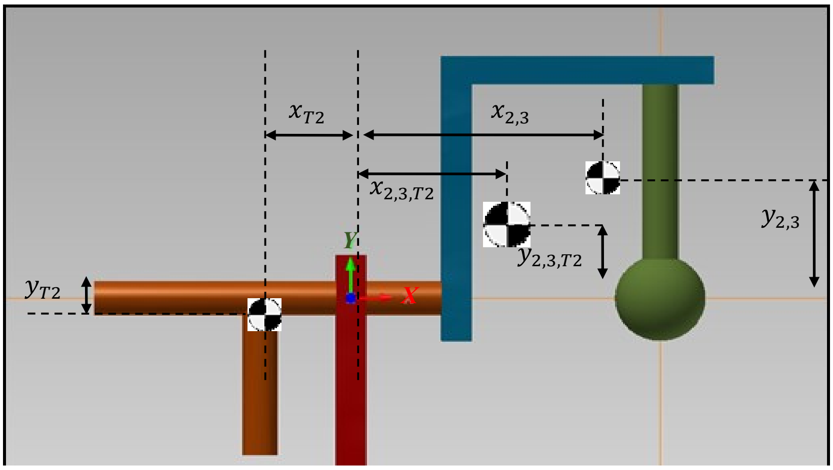

Figure 5: Center of Gravity (CG) of links to find locations of counterweights about Joint2 axis

Table 1. Theoretical and Actual Locations of CG of different links of the 3-ROSM

S.n	Link	Mass (g)	Location of CG value using Theoretical Formula (mm)		Location of CG value using Hanging Method (mm)	
			X	Y	X	Y
1	T-Extension on Link2 (T2)	68.74	-27.26	-11.94	-27.50	-9.20
2	Link2 and Link3 (2,3)	137.21	68.43	41.60	68.50	39.40
3	Link 2 and Link 3 with T-Extension 1 (2,3,T2)	205.95	36.49	27.33	36.50	29.10

Using the moment balancing equations given in Section 2.1, the location of the counterweights to achieve passive balancing were determined and the Joint2 axis was balanced. Similarly, the balancing of Joint1 axis is done in the event that the first axis has to be kept in a direction other than that of gravity. Due to space constraints, it has not been reported in this paper. With the experimental values of the counterweights locations, the counterweights were placed on the physical prototype of the mechanism, shown in Figure 3, and it was found that passive balancing was achieved when the user ceased to hold the EE.

4 Conclusion

The Authors have proposed improvements in the existing design of the 3-ROSM and have implemented the same in a physical prototype. In order to increase the adaptability of the mechanism, the T-extensions are threaded such that the counterweights can be adjusted as per the user's requirement. In order to accurately place the counterweights on the system, the CG of the links have been found practically with the use of the Hanging Method.

Future work on the 3-ROSM would involve the addition of hollow bore encoders to measure the change in joint angles. These values could then be used in various applications such as controlling viewpoints in a CAD software or a 3-axis camera mount, etc. Since the size of the prototype exceeded the available bore diameters of encoders, the authors propose the development of an integrated potentiometer to measure the joint angles. To facilitate the use of available encoders, a scaled down 3-D printed model of the 3-ROSM can be developed and tested in various applications.

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