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A NEW CONCEPT FOR RECONFIGURABLE PLANAR MOTION GENERATORS

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ABSTRACT

This paper presents a novel concept for Reconfigurable Motion Generators (RMGs) for multi-phase planar motion generation. Reconfigurable Motion Generators are a new class of mechanical devices that are designed for a specific part family and their associated motion generation tasks.

Reconfigurable Motion Generators are capable of configuration changes according to variations in the motion generation requirements. Thus, Reconfigurable Motion Generators bridge the gap between the relatively high flexibility and high cost of totally flexible machines (e.g. industrial robots) and the low flexibility and low cost of fully dedicated mechanisms (e.g. cams & linkages). Here, we propose the concept of planar Reconfigurable Motion Generators for multi-phase motion generation tasks. This paper introduces design concepts and principles for the efficient and effective synthesis of Reconfigurable Motion Generators that may be deployed in various automated manufacturing environments.

INTRODUCTION

Four-bar mechanisms have been widely used for path, function, and motion generation tasks. However, single degree of freedom (d.o.f.) closed chain mechanisms like these can only perform a single motion generation task. If there is a slight change in the required motion generation task then the whole mechanism needs to be redesigned. Moreover, the fewer number of dimensional parameters in a four-bar mechanism limits the designers options when motion defects such as branch, order, and circuit defects arise in the synthesis process, Soh and McCarthy [12].

This limitation of single d.o.f. closed chain mechanisms can be overcome by enabling the adjustment of one or more structural parameters (link lengths and pivot locations) of the mechanism. Such mechanisms have been referred to as adjustable mechanisms or adjustable linkages, Tao [13]. Adjustable four-bar mechanisms can greatly enhance the ability to generate various kinds of output motions using the same set of links. They provide not only the flexibility required in many industrial applications, but also high operational speed, high load-bearing, and high precision capabilities. Thus, they form the true middle ground between conventional closed chain mechanisms and flexible serial chain manipulators, Chuenchom and Kota [8] and Kota [7]. Chuenchom and Kota [8] called these mechanisms "Programmable Mechanisms" or "Adjustable Robotic Mechanisms (ARMs)". Chuenchom [2] introduced the concept of "soft robots" for industrial applications where a mechanism was used for different motion generation tasks by an adjustment of its parameters. Krovi et al. [10] introduced a single d.o.f. coupled serial chain (SDCSC) in order to simplify the control by coupling the inputs of the serial chain manipulator. Kim [5] discussed the idea of joint unactuation/actuation to adjust the manipulability and as a result improve the task adaptability of closed chain mechanisms. Kim and Choi [6] have discussed the idea of improved task adaptability of open/closed chain mechanisms through continuous joint mode conversion.

This paper presents a novel concept for Reconfigurable

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Motion Generators (RMGs) for multi-phase planar motion generation. Traditional hard automation linkage or cam driven mechanisms provide an extremely high speed capability at a relatively low cost. This is desirable for automation tasks that are not expected to change (i.e hard). However in automation tasks where there is a requirement for flexibility in the motion generation tasks (i.e. soft), these machines are inadequate and call for the implementation of multi degree-of-freedom serial chain manipulators.

Multi degree-of-freedom serial chain manipulators offer more flexibility and have the ability to adapt to a variety of divergent tasks, however they are expensive to procure and maintain and have relatively longer cycle times. In most industrial operations the requirements for flexibility in operations are very limited. A typical serial chain robot may be only used for a few distinct pick & place operations throughout its operational life. This results in inadequate utilization of the robot. There is a need for a new class of mechanical devices that offer the speed of hard automation mechanisms along with some degree of the operational flexibility found in serial chain manipulators. Reconfigurable Motion Generators are a new class of mechanical devices conceived to address this need.

Reconfigurable Motion Generators are capable of configuration changes according to variations in the motion generation requirements. Thus, Reconfigurable Motion Generators bridge the gap between the relatively high flexibility and high cost of totally flexible machines (e.g. industrial robots) and the low flexibility and low cost of fully dedicated mechanisms (e.g. cams & linkages). Here, we propose the concept of planar and spherical Reconfigurable Motion Generators for multi-phase motion generation tasks. This paper introduces design concepts and principles for the efficient and effective synthesis of Reconfigurable Motion Generators that may be deployed in various automated manufacturing environments.

This paper proceeds as follows. First, the motivation and objectives of RMGs are presented. Next, the reconfiguration principle is discussed. This is followed by the introduction of planar and spherical RMGs. A prototype planar RMG is presented as well. Finally, the paper concludes with a summary and a discussion of related ongoing and future works.

1 OBJECTIVE

The objective of this research is to formulate methodologies for the design of Reconfigurable Motion Generators (RMGs) for multi-phase motion generation tasks, see Fig. 1. The concept of mechanism reconfiguration is proposed for improved task adaptability, in which the geometry of a mechanism is easily altered depending on the rigid body guidance task to be accomplished. RMGs are capable of generating distinct output motions using the same set of links. The adjustment of one or more parameters of the RMG facilitates multi-phase motion generation.

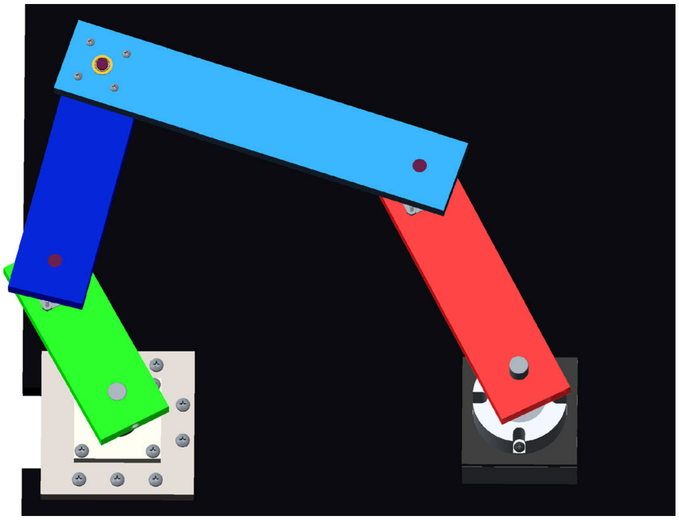

FIGURE 1. RMG: CONCEPT CAD MODEL.

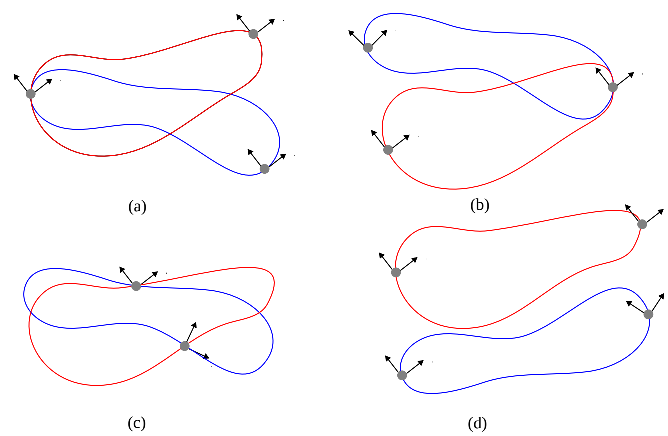

FIGURE 2. DIFFERENT TYPES OF MULTI-PHASES MOTION GENERATION TASKS.

This work proposes the utilization of revolute (R) joints for link length and pivot adjustment to achieve different configurations from the same set of links. This approach is highly favorable since revolute joints are relatively easy to manufacture and maintain. Also due to the nature of adjustment of the mechanism this methodology may be used for different types of motion generation tasks viz., (a) Common start position, (b) Common end position, (c) Common intermediate position, and (d) Distinct motion generation tasks with no common positions, see Figure 2. This technique can be applied towards the synthesis of RMGs for use in many applications involving multi-phase function, path, and motion generation tasks.

TABLE 1. COMPARISON OF SERIAL CHAIN MANIPULATORS AND CLOSED CHAIN MECHANISMS (Kota [9])

	Serial chain manipulators	Closed chain mechanisms
Advantages	Planning flexibility	High reliability
	Operational flexibility	Low cost
	Proven off-the-shelf components	Excellent repeatability
	Easier to design	High speed
Disadvantages	High cost	Lack of flexibility
	Poor reliability and repeatability	Difficult to design
	Heavy and slow	Custom construction

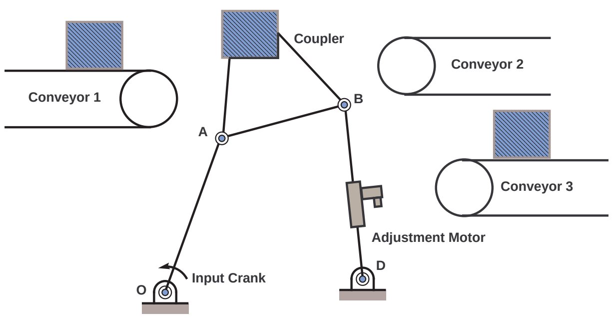

FIGURE 3. AN ADJUSTABLE PLANAR LINKAGE (Chuenchom and Kota [3]).

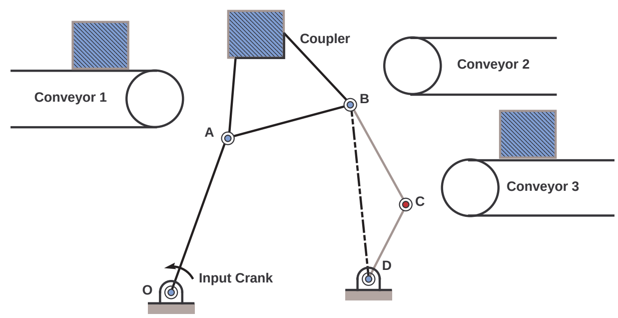

FIGURE 4. PROPOSED ALTERNATIVE DESIGN: USING A RMG.

2 RECONFIGURATION PRINCIPLE

In motion generation tasks, the objective is to calculate the mechanism parameters required to achieve or approximate a set of prescribed rigid-body positions. This mechanism design objective is particularly significant when the rigid-body must achieve a specific set of end effector positions for a specific task e.g., a pick-and-place operation.

Consider the adjustable mechanism suggested for a pick-and-place operation by Chuenchom and Kota [4] shown in Figure 3. The figure shows two different types of parts being transported from conveyor 1. Depending on the type of part being transported from conveyor 1, the mechanism is required to place the part on conveyor 2 or conveyor 3. These two distinct pick-and-place operations comprise two different rigid body guidance or motion generation tasks. The solution proposed by Chuenchom and Kota [4] for the task is an adjustable planar four-bar mechanism which can switch between the two tasks by a readjustment of the output link length by means of an adjustment motor. This gives a degree of adjustability to the mechanism and allows it to switch from one configuration to another. However, there are some drawbacks to this system due to the use of the additional actuator such as weight, cost, and complexity.

The proposed alternative shown in Figure 4 is to replace the adjustable link (BD) by an RR dyad. The resultant mechanism is a two d.o.f. five-bar mechanism. If joint C on the five-bar mechanism is locked by means of an electromagnetic clutch or brake, the five-bar mechanism loses one d.o.f. and is reduced to a four-bar mechanism with output link BD. The length of the resultant link BD can thus be adjusted by locking joint C at the desired position. Electromagnetic clutches and brakes such as shown in Figure 5 are readily available and can be used in joints where parameter adjustment is desired. This configuration has the inherent advantages of speed and ease of manufacture. Since the mechanism does not have a separate adjustment motor for readjustment of the link length it is expected to be significantly lighter and more cost-effective. We shall call these mechanisms Reconfigurable Motion Generators, based on the definition of a reconfigurable mechanism as discussed by Kuo et al. [11].

3 PLANAR RMGs

Planar four-bar mechanisms may be used for multi-phase motion generation tasks by an adjustment of link lengths and

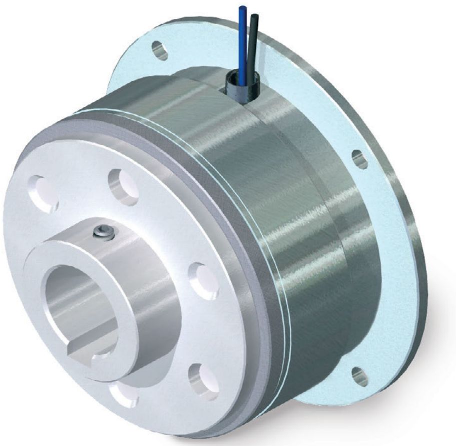

FIGURE 5. A SHAFT MOUNTED CLUTCH.

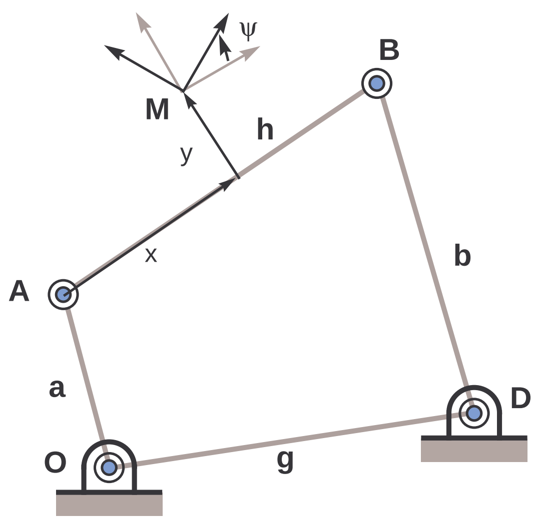

FIGURE 6. FOUR-BAR MECHANISM PARAMETERS.

pivot locations. The parameters that can be adjusted in the four-bar mechanism performing motion generation as shown in Figure 6 are,

Driving fixed pivot (**O**).
Driving moving pivot (**A**).
Driven fixed pivot (**D**).
Driven moving pivot (**B**).
Link lengths: input (**a**), output (**b**), coupler (**h**), and fixed (**g**).
The attachment of the moving body to the coupler: **M** (x, y, ψ).

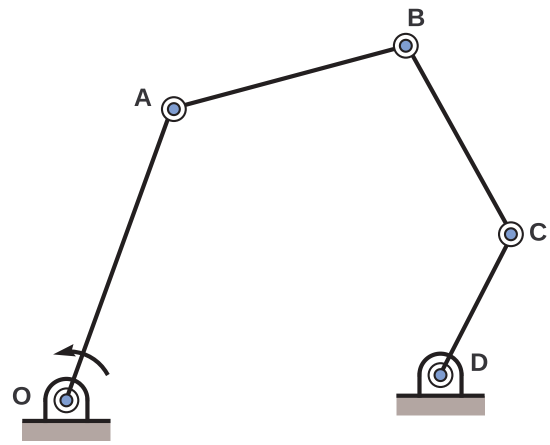

FIGURE 7. RMG: BASE CONFIGURATION.

In order to illustrate the concept of RMGs let us consider the five-bar mechanism OABCD shown in Figure 7. The mechanism is a planar two d.o.f. mechanism which requires two independent inputs. This mechanism is called the base configuration of the RMG. The five-bar mechanism can be constrained in various ways by locking or braking one of the R joints to yield a planar one d.o.f. four-bar mechanism. Thus we can obtain four different configurations of the RMG based on which joint is locked.

4 CONFIGURATIONS OF A PLANAR RMG

4.1 Configuration 1

Consider a RMG in configuration 1 as shown in Figure 8. In this configuration joint A is locked and link OB becomes the input link of the RMG. Thus, the original two d.o.f. five-bar mechanism is transformed into a one d.o.f. four-bar mechanism OBCD in which the input, output, coupler, and fixed links are OB, CD, BC, and OD respectively. The length of the input link OB may be changed by controlling the position at which joint A is locked. This facilitates control over the length of the input link OB depending on the range of $\angle OAB$. This parameter adjustment can be realized by means of a clutch or brake at joint A.

4.2 Configuration 2

Consider a RMG in configuration 2 as shown in Figure 9. In this configuration joint B is locked and link AC becomes the coupler link of the RMG. Thus, the original two d.o.f. five-bar mechanism is transformed into a one d.o.f. four-bar mechanism OACD in which the input, output, coupler, and fixed links are OA, CD, AC, and OD respectively. The length of the coupler link AC may be changed by controlling the position at which joint B is locked. This facilitates control over the length of the coupler link AC depending on the range of $\angle ABC$.

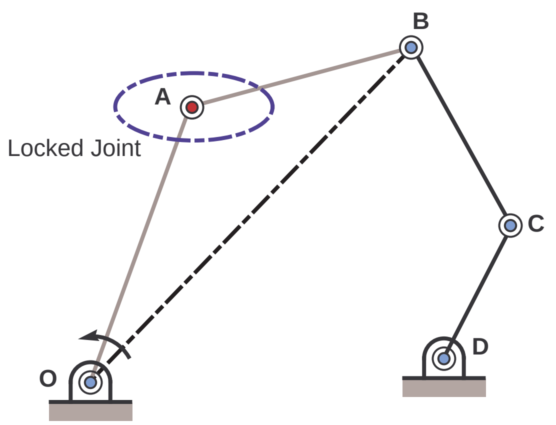

FIGURE 8. RMG: CONFIGURATION 1.

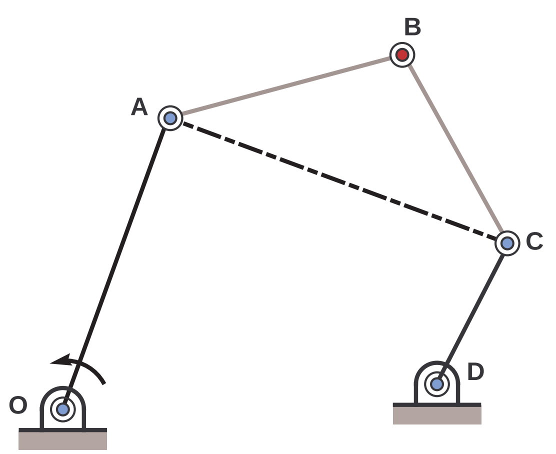

FIGURE 9. RMG: CONFIGURATION 2.

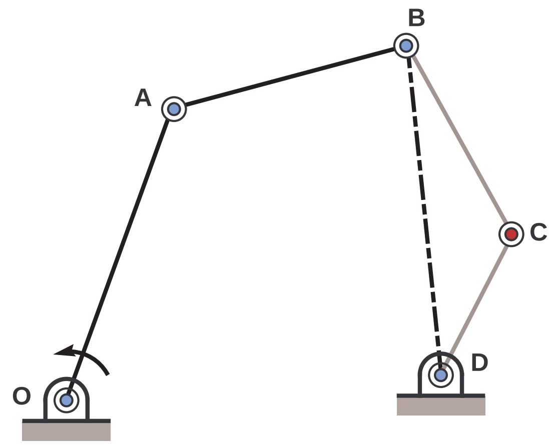

FIGURE 10. RMG: CONFIGURATION 3.

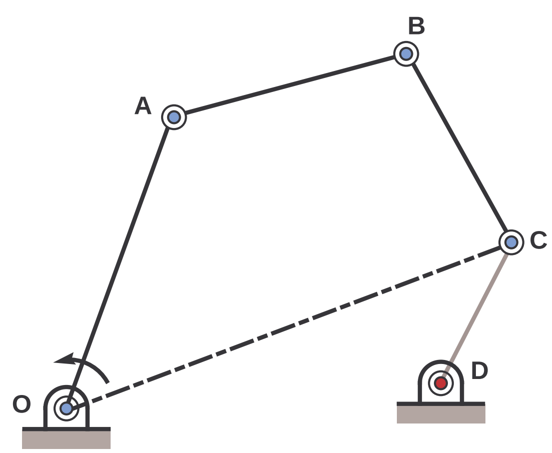

FIGURE 11. RMG: CONFIGURATION 4.

4.3 Configuration 3

Consider a RMG in configuration 3 as shown in Figure 10. In this configuration joint C is locked and link BD becomes the output link of the RMG. Thus, the original two d.o.f. five-bar mechanism is transformed into a one d.o.f. four-bar mechanism OABD in which the input, output, coupler, and fixed links are OA, BD, AB, and OD respectively. The length of the output link BD may be changed by controlling the position at which joint C is locked. This facilitates control over the length of the output link BD depending on the range of $\angle BCD$.

4.4 Configuration 4

Similarly, consider a RMG in configuration 4 as shown in Figure 11. In this configuration joint D is locked and link OC becomes the fixed link of the RMG. Thus, the original two d.o.f. five-bar mechanism is transformed into a one d.o.f. four-bar mechanism OABC in which the input, output, coupler, and fixed links are OA, BC, AB, and OC respectively. The length of the fixed link OC may be changed by controlling the position at which joint D is locked. This facilitates control over the length of the fixed link OC depending on the range of $\angle ODC$.

The four configurations of the RMG are summarized in Table 2, where **LINK** denotes the adjustable link length. From this discussion it follows that a single five-bar mechanism using one driving actuator and four relatively low cost electromagnetic brakes or clutches can be configured to perform multiple sets of motion generation tasks by simple locking or braking of its passive R joints.

TABLE 2. Different Configurations of the Planar RMG

	Link Parameter			
Configuration No.	Input	Output	Coupler	Fixed
1	**OB**	CD	BC	OD
2	OA	CD	**AC**	OD
3	OA	**BD**	AB	OD
4	OA	BC	AB	**OC**

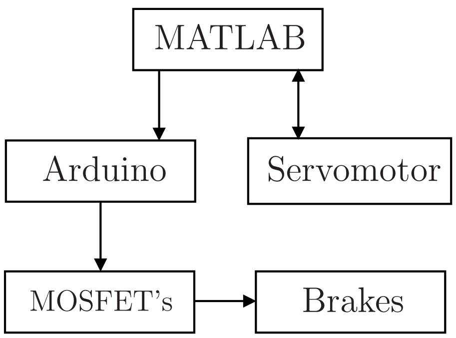

FIGURE 15. RMG: CONTROL SCHEMATIC

5 PLANAR RMG PROTOTYPE

A prototype planar RMG has been designed, fabricated, and tested. The CAD model and the physical prototype are shown side-by-side in Figure 12 and Figure 13. In Figure 14 close-ups of an RMG's moving R joint axis and its integrated brake assembly are shown.

The architecture of the control system for the protoype RMG's one actuator and four brakes is shown in Figure 15. MATLAB, running on a standard pc, is utilized as the supervisory control program. Using MATLAB's serial communication capabilities the MATLAB software communicates bidirectionally to a servo motor that actuates the prototype. In addition, another MATLAB serial interface is used to communicate in one direction from MATLAB to an Arduino Due microcontroller. The arduino is used to control four MOSFETS (metal oxide semiconductor field effect transistors) that are connected to its digital outputs. Each MOSFET is used to turn on and off one of the four brakes on the prototype.

6 SPHERICAL RMGs

The principle of a planar RMG may be extended to the spherical case by replacing the spherical P (prismatic) joint with a spherical RR dyad, see Figure 16. This approach is more attractive than the use of an adjustable spherical link as was suggested by Hong and Erdman [1] which is difficult to design and manufacture to minimize the binding and friction in the spherical P joint, see Figure 17. The spherical RMG operates on the same principle as a planar RMG. In Figure 16, the link length OB, that is to say the angle between the two lines passing through the center of the sphere and the joint axes O and A, may be controlled by locking joint A at the desired position. Thus, the two d.o.f. spherical five-bar mechanism OABCD is reduced to a one d.o.f. four-bar mechanism OBCD in which the input, output, coupler, and fixed links are OB, CD, BC, and OD respectively. Moreover, since the reconfiguration depends only on the locking of pin joints in the mechanism, the four different configurations of the spherical RMG are easily attained.

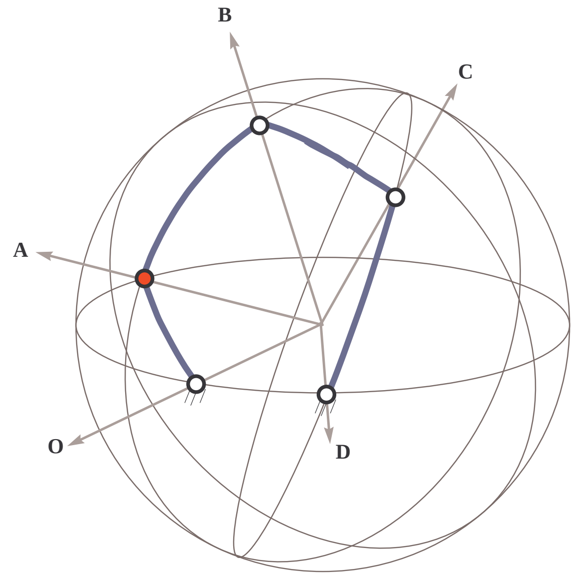

FIGURE 16. SPHERICAL RMG

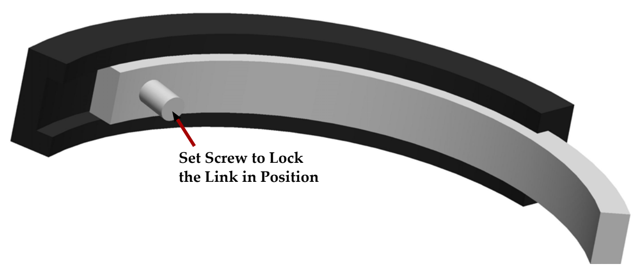

FIGURE 17. AN ADJUSTABLE SPHERICAL LINK (Hong & Erdman [1])

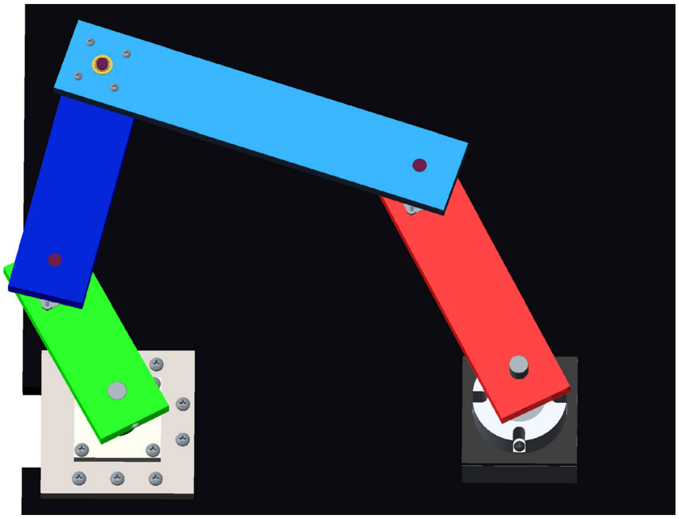
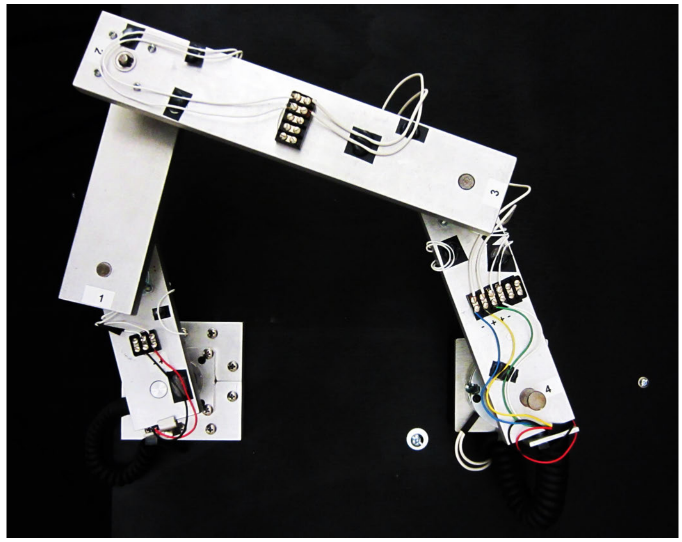

FIGURE 12. RMG: CAD and PROTOTYPE (view 1).

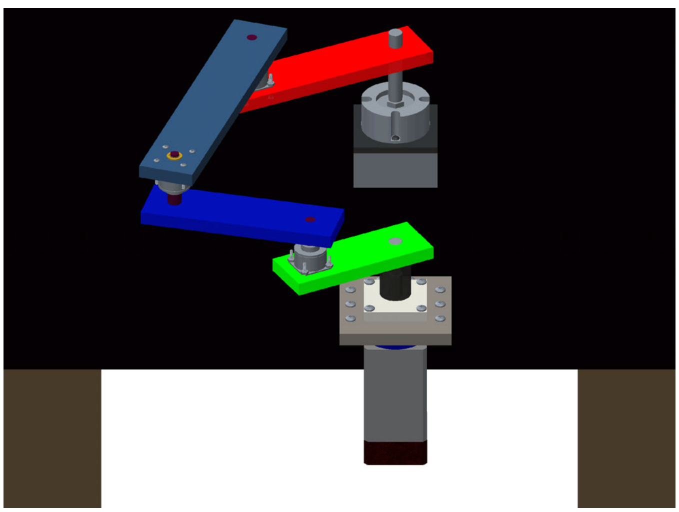
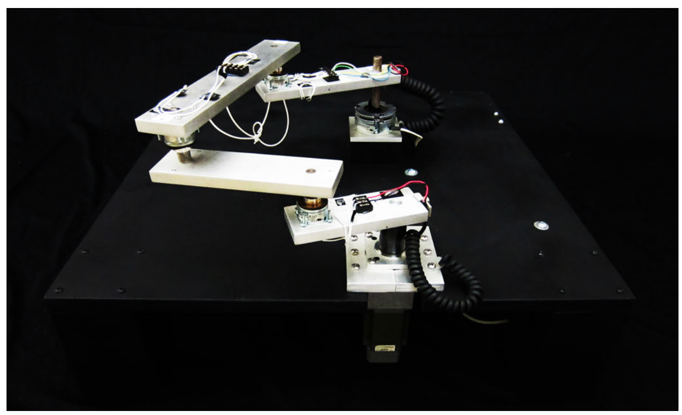

FIGURE 13. RMG: CAD and PROTOTYPE (view 2).

7 SUMMARY AND ONGOING WORK

RMGs are a new concept for a highly flexible and adaptable class of machines capable of achieving a variety of motion generation tasks. They possess the inherent advantages of closed chain mechanisms which makes them attractive for motion generation tasks involving part families of products. Future work involves the development of a general methodology for dimensional synthesis of RMGs for multi-phase motion generation. In order to attain this objective, determination of the optimum joint locking sequence and limits of attainable link lengths for each configuration need to be determined. The dimensional synthesis process also requires determining the feasibility of various configurations of the RMG to avoid motion defects such as order, branch, and circuit. These and other topics related to the synthesis, analysis, design, and simulation of RMGs are being addressed in the doctoral research currently being performed by the second author.

ACKNOWLEDGMENT

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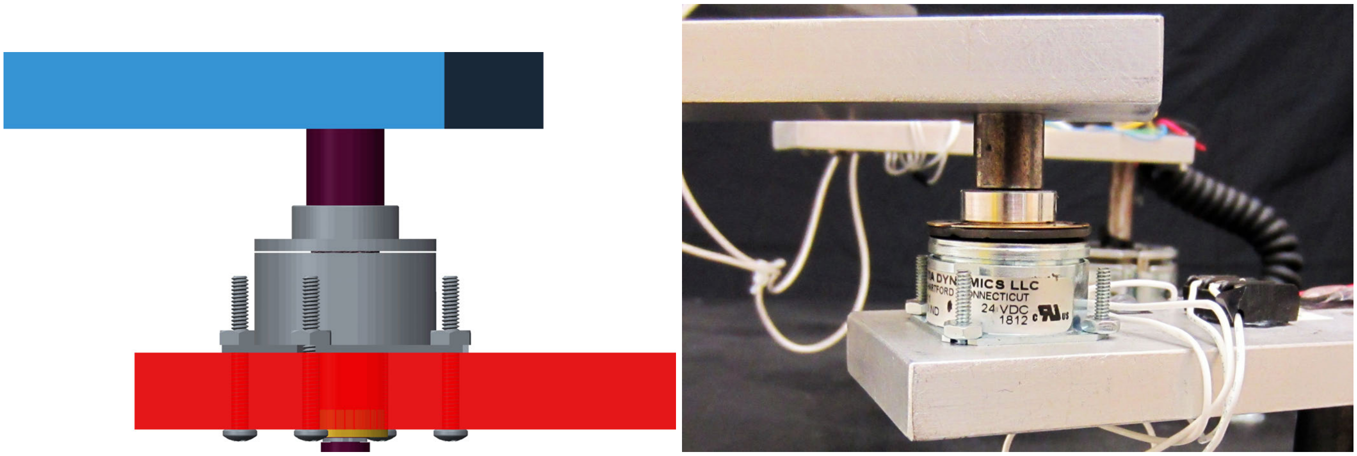

FIGURE 14. RMG: JOINT ASSEMBLY CAD and PROTOTYPE).

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