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Design and development of planar reconfigurable motion generators

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ABSTRACT

This article presents the concept of a new class of mechanical devices for multi-phase motion generation tasks. Reconfigurable Motion Generators are a new class of mechanical devices that are designed for a specific part family and their associated motion generation tasks. The research endeavors to realize a novel concept for Reconfigurable Motion Generators (RMGs) for multi-phase planar motion generation. 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 relative high flexibility and high cost of totally flexible devices (e.g., industrial robots) and the low flexibility and low cost of fully dedicated devices (e.g., cams and linkages). This paper introduces the concept of Reconfigurable Motion Generators that may be deployed in various automated manufacturing environments involving multi-phase motion generation tasks. The development, manufacturing, and testing of a prototype and the control system for a planar Reconfigurable Motion Generator based on a five-bar mechanism are discussed.

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Design for motion generation; design of planar linkages; kinematics of machines; kinematic synthesis/optimization; planar mechanism design; reconfigurable mechanisms; robotics/machine control.

1. Introduction

This article presents a novel concept for Reconfigurable 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 d.o.f. serial chain manipulators.

Multi d.o.f. 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-and-place operations throughout its operational life. This results in inadequate utilization of the robot. A brief comparison of closed chain mechanisms and serial chain manipulators is shown in Table 1, which is based on data reported in Kota and Erdman (1997). 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.

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Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/lmbd.
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Table 1. Comparison of serial chain manipulators and closed chain mechanisms.

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

RMGs are capable of configuration changes according to variations in the motion generation requirements. Thus, RMGs 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 RMGs for multi-phase motion generation tasks. This paper introduces the principle of reconfiguration for achieving different sets of motion generation tasks using brakes at the passive R joints. Some recent research results in the literature are being considered as possible future research focus areas by our RMG research team. For example, exploring the feasibility of attaching a multi-finger multi-functional gripper to an RMG (Bhattacharya et al., 2014). Another option is to use advanced NURBS-based techniques for planning RMG motion to change states and/or configurations (Sekar and Han, 2014). Finally, RMGs may serve well as feed units in the recently proposed Square Foot Manufacturing (SFM) paradigm (Grimske et al., 2014).

This paper proceeds as follows. First, the pertinent literature is reviewed. Next, the motivation and objectives of planar RMGs are presented. The reconfiguration principle is then discussed. This is followed by an introduction to planar RMGs. The development of the concept, manufacturing, and control of a prototype planar RMG is presented. Finally, the paper concludes with a summary and a discussion on the potential applications for RMGs.

2. Background and literature review

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, 2009).

These limitations of single d.o.f. closed chain mechanisms can be overcome by enabling the adjustment of one or more structural parameters (link lengths or pivot locations) of the mechanism. Such mechanisms have been referred to as adjustable mechanisms or adjustable linkages (Tao, 1964). 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 (Kota and Chuenchom, 1990; Kota, 1991). Chuenchom and Kota called these mechanisms “Programmable Mechanisms” or “Adjustable Robotic Mechanisms (ARMs)” (Kota and Chuenchom, 1990). Chuenchom 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 (e.g., link lengths and pivot locations) (Chuenchom, 1993).

Several analytical or graphical methods for the analysis and synthesis of adjustable mechanisms have been proposed in the literature. McGovern and Sandor proposed the synthesis of function and path generating mechanisms by adjusting fixed pivot locations (McGovern and Sandor, 1973a,b). This adjustment enables the mechanisms to attain two sets of precision points. A technique for the synthesis of adjustable linkages proposed by Tao and Krishnamoothy used a graphical approach to synthesize mechanisms for the generation of variable coupler curves, either symmetrical or with cusps (Tao and Krishnamoorthy, 1977a,b). Adjustable four-bar linkages were proposed by Ahmad, Naik and Amarnath, and Chang (Ahmad and Waldron, 1979; Naik and Amarnath, 1989; Chang, 2001). Krovi et al. 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 (Krovi et al., 2002). Peng and Sodhi developed an optimal synthesis method for multi-phase continuous path generation of adjustable planar four-bar linkages (Peng and Sodhi, 2010). Chanekar and Ghosal described an optimization-based method for the synthesis of adjustable planar four-bar, crank-rocker mechanisms (Chanekar and Ghosal, 2013). Kim discussed the idea of joint unactuation/actuation to adjust the manipulability and as a result improve the task adaptability of closed chain mechanisms (Kim, 1998). Kim and Choi have discussed the idea of improved task adaptability of open/closed chain mechanisms through continuous joint mode conversion (Kim and Choi, 1999). And Li and Dai present several possible interchanges of five-bar and four-bar mechanisms (Li and Dai, 2012).

There has also been some research on adjustable slider-crank mechanisms. Zhou and Ting have proposed adjustable slider-crank mechanisms for multiple path generation (Zhou and Ting, 2002). Russel and Sodhi have investigated design methodologies for multi-phase motion, function, and path generation of slider-crank mechanisms (Russell and Sodhi, 2005a,b). Adjustable three-dimensional mechanisms have been investigated by Hong and Erdman (2005). Shoup presented a technique for the design of an adjustable spatial slider crank mechanism to be used as a variable displacement pump or compressor (Shoup, 1984). The study has been extended to more complicated mechanisms by Russel and Sodhi, they studied the kinematic synthesis of adjustable RSSR-SS mechanisms for multi-phase finite and multiply separated positions (Russell and Sodhi, 2003). There have been various examples of programmable mechanisms investigated by researchers. Du and Gue designed a metal-forming press based on a two d.o.f. programmable seven-bar mechanism driven by a large constant speed motor and a small servomotor (Du and Guo, 2003). Pennock and Israr have investigated the kinematics of an adjustable six-bar linkage for use as a variable-speed transmission (Pennock and Israr, 2009). Soong and Wu suggested a new method for designing a variable coupler curve four-bar mechanism with one link replaced by an adjustable screw-nut link driven by a servomotor (Soong and Wu, 2009). Different coupler curves were obtained by adjusting the length of the adjustable links and controlling the angular displacement of the driving link. In preliminary work, Larochelle and Venkataramanujam first introduced the concept for a novel class of machines called Reconfigurable Motion Generators (RMGs) that could be configured to perform multiple sets of motion generation tasks by a simple locking or braking of their passive R joints (Larochelle and Venkataramanujam, 2013; Venkataramanujam and Larochelle, 2014; Venkataramanujam, 2014).

3. Objective

The objective of this research effort is to investigate methodologies for the analysis, synthesis, and manufacture of a new class of machines called Reconfigurable Motion Generators (RMGs). The objective of this article is to present the development of a concept for planar RMGs. Toward this end, the manufacture of a planar RMG prototype, the design of its control system, and the testing and evaluation of the prototype have been described. This work is part of an effort to develop low d.o.f. mechanisms capable of performing tasks that are currently performed by serial chain manipulators with higher degrees of freedom. 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.

This work proposes the utilization of revolute (R) joints for link length and pivot adjustment to achieve different one d.o.f. four-bar mechanisms from a single two d.o.f. five-bar mechanism. This approach is highly favorable compared to the use of prismatic joints since revolute joints are relatively easy to manufacture and maintain. Moreover, prismatic and screw joints require a separate actuator for

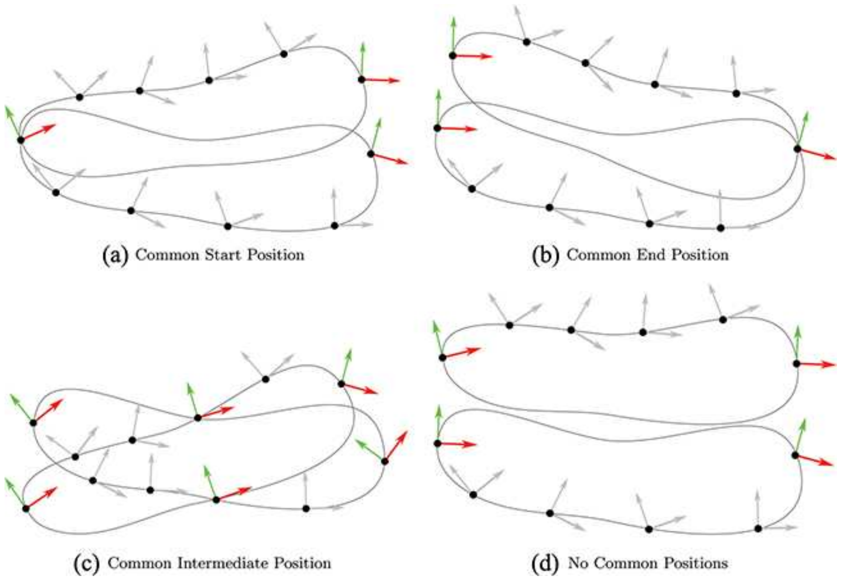

Figure 1. Different types of multi-phase motion generation tasks.

readjustment. This methodology may be used for different types of multi-phase motion generation tasks, see Fig. 1. Figure 1(a) shows the case in which parts are moved from a common start position to two different end positions. Figure 1(b) shows the case in which parts are moved from different start positions to a common end position. Figure 1(c) shows the case in which parts being moved have distinct start and end positions with common intermediate positions. Figure 1(d) shows the case in which parts being moved have distinct start and end positions with no common intermediate positions. This technique can be applied toward the synthesis of RMGs for use in many applications involving multi-phase function, path, and motion generation tasks. Finite position synthesis algorithms can be used to determine the dimensional parameters of the four-bar mechanism that can attain the desired motion generation tasks (Erdman et al., 2001; Norton, 2008). Once the four-bar mechanisms that can attain the two sets of motion generation tasks are determined, they can be used to synthesize an RMG that can attain the two four-bar mechanisms as two states of the same configuration or two different configurations by locking/unlocking its joints as desired. The *configuration* of an RMG is defined by the joint being locked (e.g., in Fig. 3 the RMG is in Configuration 3). The *state* of an RMG is defined by the length of the virtual link that subtends the locked joint (e.g., in Fig. 3 the state of the RMG is defined by the length of link BD, which subtends the locked joint C).

4. Reconfiguration principle

In dimensional synthesis, 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 prescribed 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 shown in Fig. 2 (Chuenchom and Kota, 1997). 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 for the task is an adjustable planar four-bar mechanism

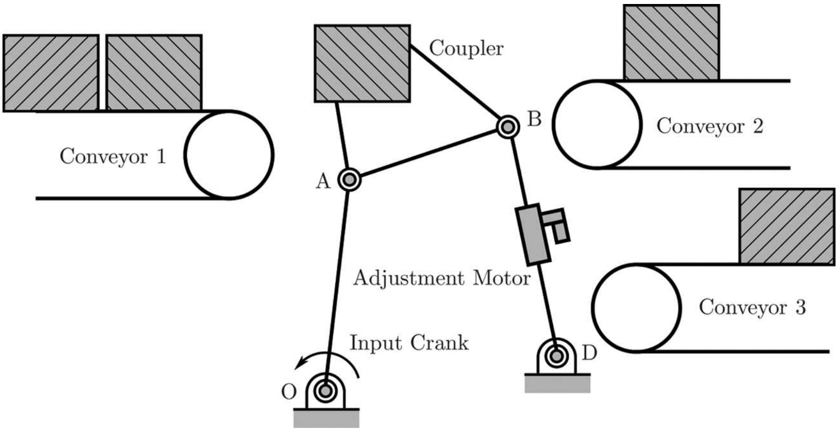

Figure 2. An adjustable planar linkage.

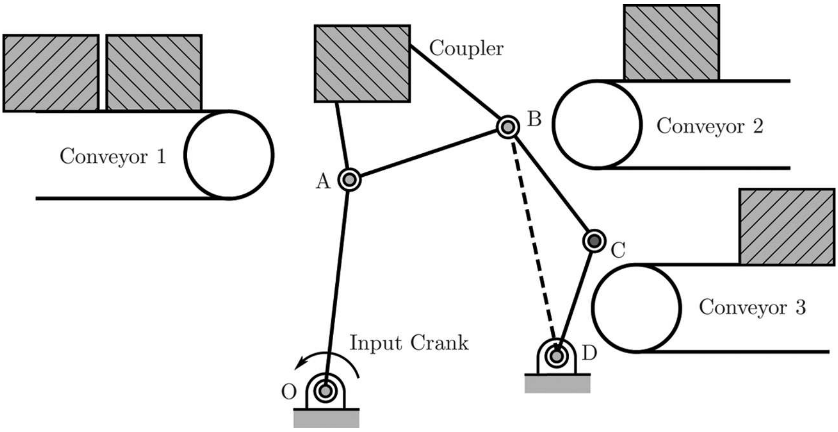

Figure 3. Reconfigurable motion generator.

that 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 an additional actuator such as weight, cost, and complexity.

The proposed alternative shown in Fig. 3 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, e.g., 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 shown in Figs. 10 and 11 are readily available and can be used in joints where parameter adjustment is desired. This arrangement of links where brakes are incorporated at the joints 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 due to lower mass of links and consequently facilitate higher speeds and lower inertia. We shall call these mechanisms Reconfigurable Motion Generators, based on the definition of a reconfigurable mechanism as discussed by Kuo et al. (2009).

4.1. Definition of a planar RMG

A *planar reconfigurable motion generator* is defined here as a planar five-bar mechanism that is driven by one actuator and having each of its four passive joints equipped with an electromagnetic brake.

5. Base configuration

Planar four-bar mechanisms may be used for multi-phase motion generation tasks by an adjustment of link lengths and pivot locations. The parameters that can be adjusted in the four-bar mechanism performing motion generation as shown in Figs. 4 are,

- Driving fixed pivot (O).
- Driven fixed pivot (D).
- Link lengths: input (a), output (h), and coupler (b)
- The attachment of the moving body to the coupler: $\mathbf{M}$ (x, y, α).

In order to illustrate the concept of RMGs, let us consider the five-bar mechanism OABCD shown in Fig. 5. The mechanism is a planar two d.o.f. five-bar mechanism that requires two independent inputs. This mechanism is called the base configuration of the RMG. The five-bar mechanism can be constrained

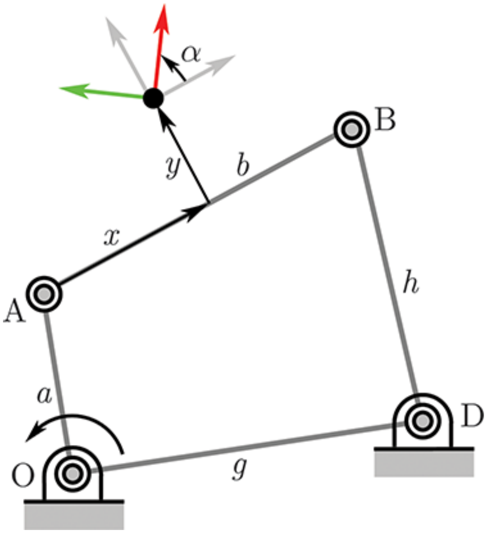

Figure 4. Four-bar mechanism parameters.

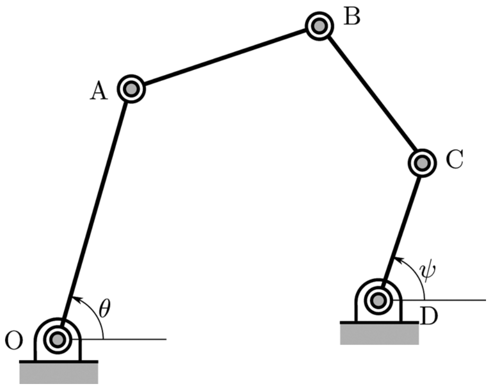

Figure 5. RMG: base configuration.

in five different ways by locking or braking one of the R joints to yield a planar one d.o.f. four-bar mechanism. The joints that can be locked are O, A, B, C, and D, respectively, giving us five different one d.o.f. four-bar mechanisms. Joint O forms the driving fixed pivot of the mechanism, thus it is never locked. Thus, four different configurations of the RMG may be obtained based on the joint being locked.

6. RMG: Configurations

The planar RMG is a two d.o.f. freedom five-bar mechanism that can be transformed into four different one d.o.f. four-bar mechanisms or configurations by locking one of the joints at A, B, C, or D by means of brakes, see Fig. 6. The link parameters of the four-bar mechanism thus formed are determined by the position at which these joints are locked.

The magnitude (length) of the adjustable link determines the state of the RMG. Reconfigurable Motion Generators can perform distinct motion generation tasks in different configurations as well as different states in the same configuration. Thus, if two distinct sets of motion generation tasks are to be achieved, four-bar mechanisms can be synthesized for each of the desired tasks. The two four-bar mechanisms that are obtained may be considered to be different configurations and states of the RMG that have to be achieved. The two four-bar mechanisms are the starting points for the design of an RMG that can achieve both the desired motions by simply switching configurations and states. Thus, the appropriate RMG may be synthesized to achieve both the sets of motion generation tasks by appropriately switching on/off the brakes.

Consider an RMG in configuration 1 shown in Fig. 6(a). 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

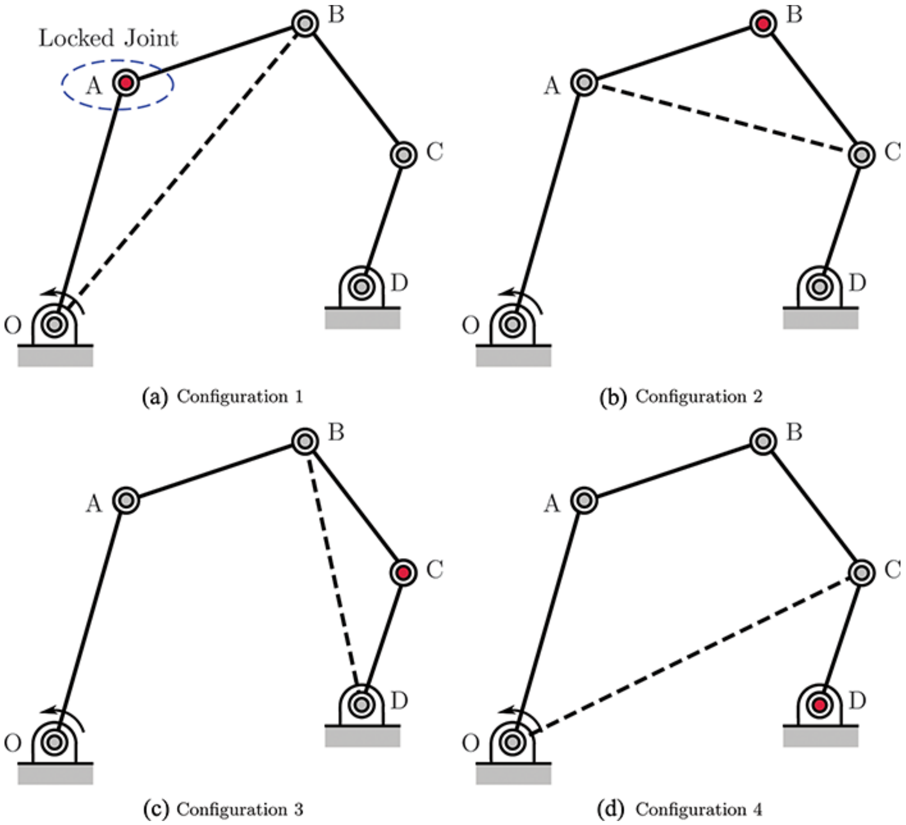

Figure 6. Different configurations of a reconfigurable motion generator.

Table 2. Mechanism parameters for configurations of a reconfigurable motion generator.

Config. no.	Input	Output	Coupler	Fixed	Locked joint	Adjustable angle
1	$\underline{OB}$	CD	BC	OD	A	∠OAB
2	OA	CD	$\underline{AC}$	OD	B	∠ABC
3	OA	$\underline{BD}$	AB	OD	C	∠BCD
4	OA	BC	AB	$\underline{OC}$	D	∠ODC

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 ∠OAB. This parameter adjustment can be realized by means of a clutch or brake at joint A. Similarly, configurations 2, 3, and 4 may be obtained by locking joints B, C, and D, respectively.

The four configurations of the RMG are summarized in Table 2, where $\underline{\text{LINK}}$ denotes the adjustable link. A single five-bar mechanism using one driving actuator and four relatively low-cost electromagnetic brakes can be configured to perform multiple sets of motion generation tasks by a simple locking or braking of its passive R joints. The implementation of brakes at the joints allows the RMG to switch configurations without the need for manual adjustment.

7. Manufacture and assembly of prototype

A prototype planar RMG has been designed, fabricated, and tested in order to validate the concept. The CAD model and the physical prototype are shown in Figs. 7 and 8. In Fig. 9, close-ups of an RMGs moving R joint axis and its integrated brake assembly are shown. The design and kinematic analyses were carried out in PTC Creo Parametric (PTC Inc., 2013). The parts and link lengths were selected based upon the smallest available brakes possessing the adequate braking torque to lock the desired joint. The links are built from aluminum alloy bar with 0.5 × 2.5 inch cross-section.

The RMG prototype consists of five links (a, b, c, h, g) connected serially to each other forming a closed chain. Joint O is the input fixed pivot actuated by an AC servomotor. Joints A, B, and C include flange mounted brakes (FB 11) shown in Fig. 10 (Inertia Dynamics, Altra Industrial Motion, Inc, 2013a). Joint D includes a spring applied brake (SAB 20) shown in Fig. 11 (Inertia Dynamics, Altra Industrial Motion, Inc, 2013b). The link lengths chosen for the prototype are shown in Table 3. The links are arranged in

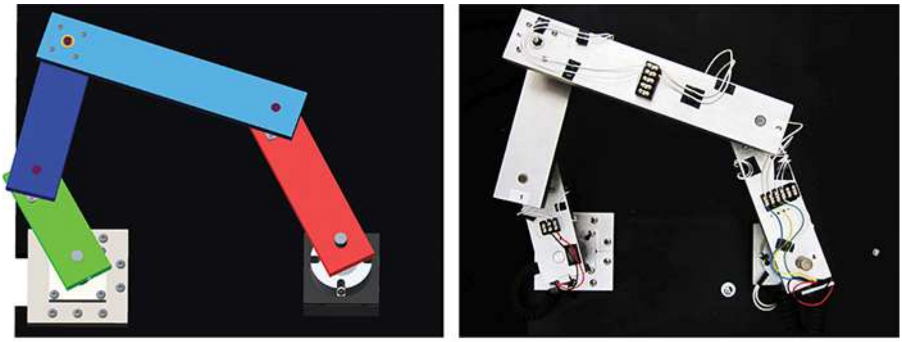
(a) CAD (b) Prototype

Figure 7. RMG: CAD model and prototype (view 1).

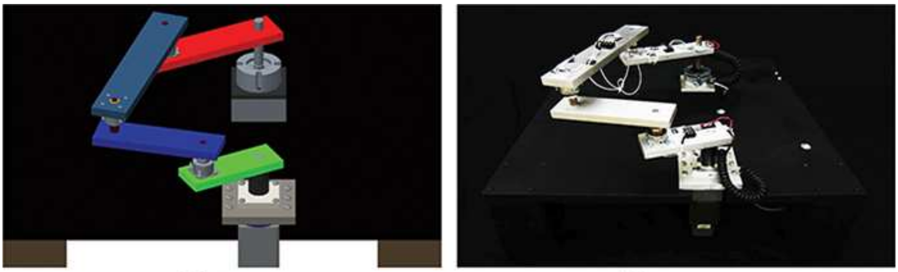
(a) CAD (b) Prototype

Figure 8. RMG: CAD model and prototype (view 2).

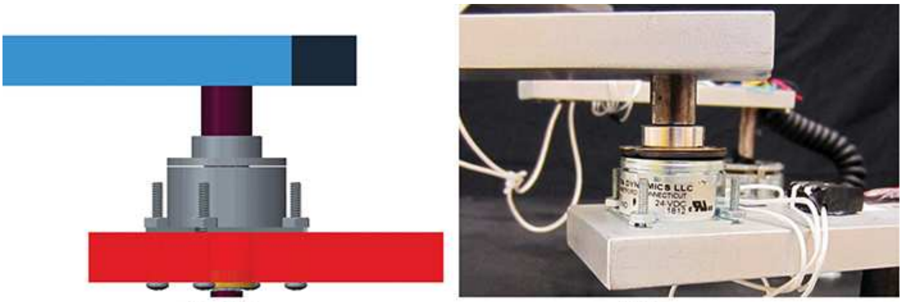
(a) CAD (b) Prototype

Figure 9. RMG joint CAD model and prototype.

Figure 10. Flange mounted brake (FB 11).

parallel planes to avoid collisions when the RMG changes configurations during the course of operation. The stacking order for the parallel planes containing the links is shown in Table 3 where 1 represents the link closest to the base plane and 4 represents the link farthest from the base plane. In addition, the heights of the parallel planes containing the links with respect to the base plane are shown.

Figure 11. Spring applied brake (SAB 20).

Table 3. Link lengths for the prototype RMG

Link	Symbol	Length (in.)	Stacking Order	Height (in.)
Input	*a*	3.45	2	2.795
Coupler 1	*b*	5.00	3	4.757
Coupler 2	*c*	8.75	4	6.719
Output	*h*	5.75	3	4.757
Ground	*g*	10.50	1	0.000

8. RMG: Control

This section presents the design of the control system for the RMG prototype. The RMG is actuated by means of a Cool Muscle AC Servo Motor at the input fixed pivot (O) (Muscle Corporation, 2009). The Cool Muscle is a closed loop servo motor system with an integrated encoder, driver, and a controller powered by an external 24V DC power supply. The SAB 20 on the output fixed pivot (D) of the RMG is also powered by the DC power supply. The flange mounted brakes (FB 11) attached to pivots A, B, and C on the RMG are powered by Li-Ion batteries (9 V–500 mAh). The voltage from the batteries is increased to the operating voltage of the flange mounted brakes (24 V) by means of two Pololu step-up voltage regulators used in series to achieve the required voltage (Pololu Corporation, 2013). The control of the brakes on the RMG is achieved by an Arduino Leonardo microcontroller (SA, 2013).

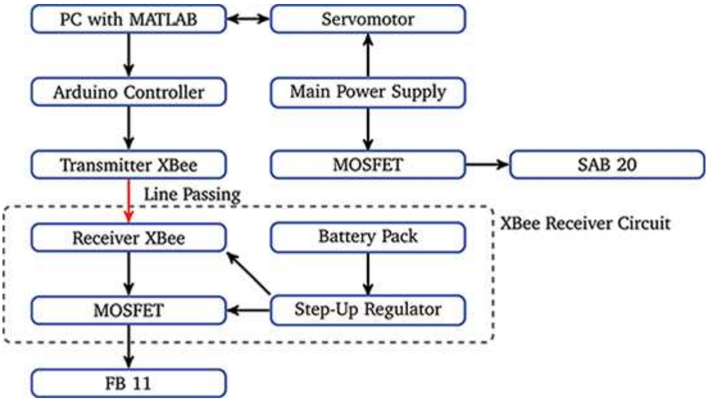

Figure 12. RMG wireless control schematic.

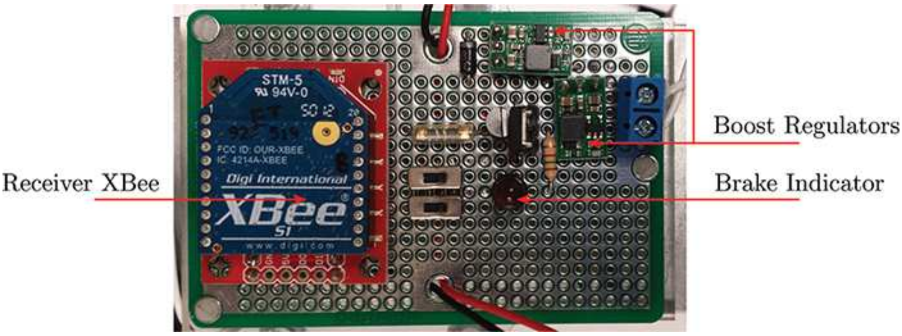

Figure 13. XBee receiver circuit.

The architecture of the control system for the prototype RMG is shown in Fig. 12. MATLAB, running on a standard PC, is utilized as the supervisory control program (The MathWorks Inc., 2013b). Using MATLAB's serial communication capabilities the PC communicates bi-directionally with the servomotor that actuates the RMG. In addition, another MATLAB serial interface is used to communicate in one direction from MATLAB to an Arduino Leonardo microcontroller using the ArduinoIO Package (The MathWorks, Inc, 2013a). The Arduino IO Package consists of a MATLAB API on the host computer and a server program that runs on the Arduino. A digital on/off signal is sent to the wireless transmitter XBee via the Arduino microcontroller. The transmitter XBee passes the digital signal sent by MATLAB to the receiver XBees on pivots A, B, and C. This is achieved by Digital Input/Output (DIO) "Line Passing," which facilitates the transmission of a digital signal from the DIO of the transmitter XBee to the DIO of the receiver XBees mounted on the links, see Fig. 13.

The MATLAB code consists of two functions to facilitate communication with the servomotor and brakes, respectively. **MoveServo(CM, position, speed)** communicates bi-directionally with the servomotor, where the input parameters are Servomotor identifier, desired position, and servomotor speed. **BrakeInput(apin, a, timepause)** communicates unidirectionally with the brakes. The input parameters to the function are Arduino pin identifier, Arduino Matlab object, and time between braking actions, respectively.

9. RMG: Testing

This section describes the testing of the planar RMG prototype. The planar RMG prototype was programmed to switch configurations as well as switch states in the same configuration. The planar RMG is started in its initial configuration with the input angle θ at 171 degrees and the output angle ψ at 133 degrees, see Fig. 5. Both the input and output angles were selected through trial and error to provide a Grashof crank-rocker mechanism as the initial configuration for the RMG prototype to allow for a complete rotation of the input link. The RMG starts in configuration 4 with joint D locked, see Fig. 6(d) and has a constant angular velocity of 90 rad/min.

9.1. RMG: Switching configurations

Starting from the initial configuration, the input link (crank) undergoes three revolutions in the clockwise direction. The RMG in configuration 4 forms a crank-rocker mechanism. After moving back to the initial state joint D is unlocked and then joint B is locked. The RMG is now in configuration 2, see Fig. 6(b). This configuration is also a crank-rocker mechanism. The crank now undergoes three revolutions before coming to a stop in the initial configuration. It may be noted that the coupler (AB) follows distinct sets of motions in each of the configurations. A video of the RMG prototype switching configurations is available at http://youtu.be/GnWpI6MtFnQ.

9.2. RMG: Switching states in the same configuration

Starting from the initial configuration, the input link (crank) undergoes three revolutions in the clockwise direction. The RMG in configuration 4 forms a crank-rocker mechanism. After moving back to the initial state joint D is unlocked and joint B is locked. The RMG is now in configuration 2, see Fig. 6(b). This configuration is also a crank-rocker mechanism. The crank now undergoes three revolutions before coming to a stop in the initial configuration. In configuration 2, the crank is rotated through an angle of 38.57 degrees in the clockwise direction, joint B is now unlocked and joint D is locked to switch the RMG to configuration 4. In configuration 4, the RMG now forms a crank-rocker mechanism, with a different magnitude for the ground link length (OC). It may be noted that the coupler (AB) follows distinct sets of motions in each of the two states in configuration 4. A video of the RMG prototype switching states in configuration 4 is available at http://youtu.be/EXwoxO4pkNg.

10. Conclusion

In this article, the concept of a new class of mechanical devices for multi- phase motion generation tasks has been described. The introduction of brakes at the passive R joints has been suggested for reconfiguration to achieve different sets of multi-phase motion generation tasks. A planar RMG prototype has been manufactured and tested. The prototype RMG demonstrates the proposed methodologies for generation of multi-phase motions using brakes at the passive R joints. Given the simplicity of structure and control of the proposed RMG, it has potential applications in repetitive multi-phase motions having only a slight change. Reconfigurable Motion Generators have the potential to replace the current complex and expensive serial chain robots and offer a less expensive and robust design that can be used in pick-and-place operations in industry.

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