Application of a Single Actuator Multiple Manipulation (SAMM) Mechanism

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ABSTRACT
Multi-Degree-Of-Freedom (MDOF) motion in a system normally requires one actuator per Degree-Of-Freedom (DOF) for position control. With the use of a Single Actuator Multiple Manipulation (SAMM) mechanism, it is possible to centralize the control of an entire MDOF system to a single actuator.

For slow systems that allocate a low duty cycle to multiple actuators, a SAMM mechanism can yield a cheaper, more efficient design as it utilizes more of an actuator's potential over the lifetime of the system. As the number of DOFs increases, a SAMM mechanism can also significantly reduce the total actuator weight of a system.

A SAMM mechanism can be created by designing individual modules to transfer the bidirectional rotation of an actuator to each DOF. By arranging these modules around an actuator, each can be activated and controlled. The prototype described in this paper uses an oscillating ratchet mechanism to facilitate this activation.

Keywords

Actuation, Efficiency, Design, Multi-degree-of-freedom

1. INTRODUCTION
In the wake of a growing interest in centralizing control and minimizing actuator size, there have been many valid proposed approaches for achieving MDOF motion from a lower amount of actuators [1]. It has been previously shown that, with the use of clutches, a "Uni-drive modular robot" can be created to drive many DOFs from one central rotating axis [2]. It has also been shown that with a vibrating transducer exciting the natural frequencies of resonators, many DOFs can be simultaneously activated [3]. With these examples, MDOF motion was achieved, but at the cost of some added complexity. In the case of the Uni-drive solution, secondary actuation was needed to activate each DOF in the form of a clutch mechanism. In the case of the vibrating transducer, the constant connection of the channels to the central vibrating actuator raises the possibility of cross-talk amongst the DOFs. The simplicity of a SAMM mechanism's selective activation of modules allows it to adequately mimic MDOF motion through the use of only gear trains and an oscillating ratchet mechanism.

In order to prove the viability of the SAMM concept, it is necessary to design a working prototype to transfer the motion of a single motor to multiple output shafts. Such a prototype provides insight into the Size, Weight, and Power (SWaP) savings of a SAMM mechanism in comparison with traditional DOF manipulation mechanisms.

2. PROTOTYPE DESIGN OVERVIEW

2.1 General Design
For simplicity, a 4 DOF prototype was developed with a ratchet as the power transmission mechanism and a worm gear as a locking mechanism for each module as shown in Figure 1.

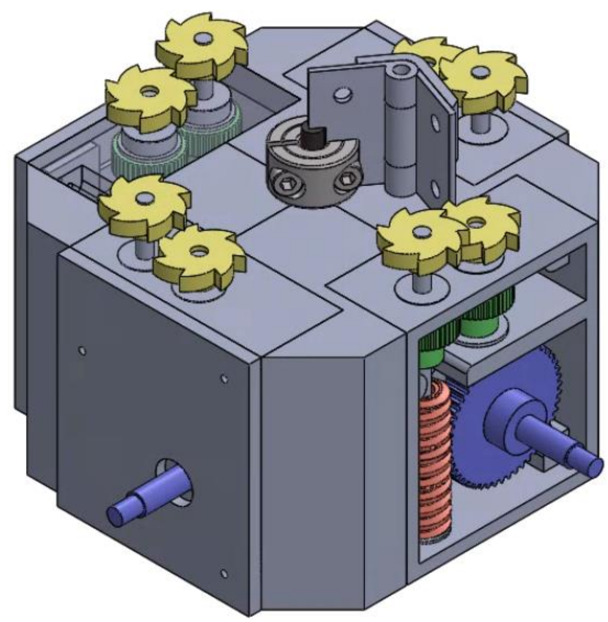

Figure 1. A full assembly CAD model of the 4 DOF prototype SAMM mechanism. The four modules exhibit rotational symmetry with respect to the motor shaft. The cover of one module has been removed for better visibility.

2.1.1 Stepper motor

To control a MDOF system with one actuator, a simple solution is to actuate each DOF one at a time in rapid succession. The prototype configuration seen in Figure 1 was chosen as a proof of concept for the SAMM design. For this chosen prototype, a motor must rapidly turn on and off in a controlled and accurate manner. The motor starting torque required for this process suggests that a stepper motor should be chosen as the input actuator over an AC motor, DC motor, or another rotational actuator.

2.1.2 Ratchet/Gear Interfacing

The chosen mechanism for power transmission relies on a ratchet shaft to activate the desired DOF while rotating in the clockwise direction, and leave input gears undisturbed while traveling in the counterclockwise direction. This ratchet is a simple, lightweight option for the power transmission; it also presents the advantage of low cost for replacement of the interfacing components.

2.1.3 Circular Module Arrangement

Individual modules for each DOF facilitate the translation of the motor's oscillations into rotations in the output shafts. These modules are arranged in a circle around the motor to create a sturdy design that can be scaled to control a different number of DOFs.

2.2 Ratchet Design

2.2.1 Hinge Design

The physical ratchet in the prototype shown previously in Figure 1 consists of a spring-loaded hinge that favors an open configuration. This hinge is attached to the motor shaft. Its angle is restricted by a plate. By adjusting the angle of the restricting plate, the radius of the ratchet arm can be adjusted.

2.2.2 Input Gear Design

The contour of the input gear teeth is flat to catch the ratchet arm while it rotates in the clockwise direction. When the ratchet traverses in the counterclockwise direction, it meets with the smooth contour on the back of the teeth. This helps the hinge to depress and pass over the gear without rotating it.

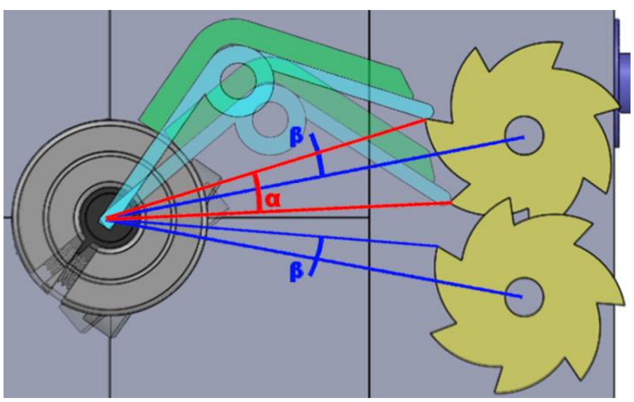

Figure 2. A top view of the angle of rotation provided by the motor to move one tooth of the input gear. This 14.93 degree rotation in the motor shaft (denoted by angle α) produces approximately 1.29 degrees of rotation in the output shaft. The angle β is the dephase angle of the two input gears.

2.2.3 Avoiding Interference

As shown in Figure 2, the number of teeth on the input gear has been optimized so that the adjacent tooth is left past the interference point after each oscillation of the ratchet. This is important to avoid possible locking of the mechanism. All input gears have the same angle relative to a radial line from the motor shaft to the outside diameter of the input gears. This means there will be a small dephase of the position of the input gears for the same DOF module. If more DOF's are added, the ratchet arm length will have to be increased and the mentioned dephase angle, β, seen in Figure 2, will have to be adjusted.

2.3 General Module Design

For actuation of each DOF, there is a module which consists of 2 spur gears, 4 bearings, 3 shafts, and a worm gear coupling. This module design is shown in Figure 3.

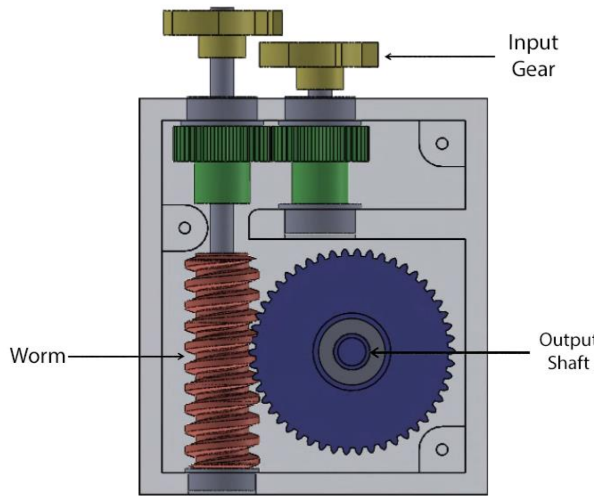

Figure 3. A front view of a prototype module showing the input gears, gear train, and output shaft. This module is used to convert the rotation of a motor into rotation in the output shaft.

The modularity of the mechanism allows for easy adjustments to the number of DOFs needing control. Each module must be controllable in both direction and non-back-drivable when not being activated. The non-back-drivable nature of the modules removes the need for clutches or secondary actuators seen in other architectures [4].

2.3.1 Bidirectional Design

Due to the use of a ratchet mechanism for module activation, it is necessary to have an input gear for each direction of rotation. The first of the two gears applies its rotation directly to the rest of the gear train. The second input gear first applies rotation to a gear coupling which rotates the rest of the gear train in the opposite direction.

2.3.2 Non-back-drivable Design

For the prototype module shown in Figure 3, the problem of non-back-drivability is solved by a worm-gear coupling. The threads of the worm can drive the gear when rotated, producing a rotation in the output shaft. When a rotation is instead applied to the output shaft, the threads of the worm hold the gear in place.

2.3.3 Prototype Capabilities

In the current configuration of the prototype module, the output ratio of the gear train is 40:1. With the seven teeth of the input gears, one full rotation of the output shaft is produced with 280 oscillations of the ratchet mechanism. The current design favors high torque output and high resolution of rotation for precise control as opposed to increasing the speed of output rotation. This lowers the size of the motor needed to move large systems.

3. DISCUSSION

The state of current technology provides an inherent limitation in the number of applications available for a SAMM mechanism. The prototype design has also taken on additional limitations in the realms of part selection and ease of design in an attempt to make a fully functional prototype that is both easy to assemble and appealing to potential markets. In future research, the miniaturization of a SAMM mechanism can introduce potential microelectromechanical systems (MEMS) applications.

3.1 Improvement of Design

The modularity of the prototype design implies an inherent scalability to different numbers of DOFs. It is important to explore the compaction ratio in comparison with multiple actuators as well as the maximum torque, speed, and efficiency that can be achieved. Other areas of improvement are the housing design and the power transmission mechanism.

3.1.1 Part Selection and Housing Design

This initial prototype is based on 3D printable and market-available parts. 3D printing has become an attractive option in combination with topology optimization to maximize structure stiffness while minimizing weight, which is attractive for the aerospace industry. The optimized structure may contain complex contours which are unachievable or cost prohibitive for traditional subtractive manufacturing and injection molding. For the purpose of showing the mechanism, topology optimization has not been applied to the structure. For a more compact and lightweight design, smaller components could be specially fabricated, but this will significantly increase the price unless mass production is organized. For the purposes of mass production, depending on the application, it is important to compare other methods of manufacturing such as injection molding and subtractive manufacturing to investigate which method is optimal.

As a fast prototype, the frame of the mechanisms was developed using additive manufacturing, which gives a low prototype cost, but increases the overall volume compared with other material alternatives. The use of 3D printing technology also allows the development of a variety of support structure configurations.

The components chosen to build the prototype were selected as a function of size, price, and availability in the future to create a scalable, cheap, and simple design that can be easily adopted in several markets where speed is not a priority. Among these markets are closed-circuit television cameras, domotics, robotics, toys, advertisement, space, research, and others.

The efficiency and weight of the system could be improved by the use of a DC Motor with a more sophisticated control system; the only setback would be the increase of price. The use of a stepper motor, depending on the given speed and torque values, may present the problem of resonance if the speed is coincident with the motor's natural frequency.

3.1.2 Introduction of a Cam Interface

As previously mentioned, the interface between the motor shaft and the gearbox input shaft is a ratchet mechanism, in which the tip of the ratchet relies on friction to slide over the tailored, 3D printed gears. The interface for this configuration has the advantage of fewer components, less weight, and easy assembly, but has a diminished lifespan due to abrasion of the interfacing components. The abrasion problem can be overcome with a low friction interfacing surface, the use of lubrication, or a material resistant to abrasion like a magnesium alloy. An alternative to the current interface can rely on a small bearing to roll over a modified gear contour that accounts for the bearing radius instead of the tip of the ratchet. This is an option that will increase the lifespan of the critical component, but will be directly affecting weight, recurrent fabrication costs, and will increase the inertia the shaft has to overcome each time there is a change in direction. The latter will minimally affect the motor life and the energy consumption of the mechanism.

3.2 Design Disadvantages

The compactness can decrease the total actuator volume and mass in a MDOF system, but the conversion to a SAMM mechanism introduces the main drawbacks of low speeds and non-simultaneous DOF actuation in applications. These drawbacks can be neglected for applications in slow, low duty cycle environments, as the delayed in DOF response would be outweighed by the extended wait time between actuations.

4. CONCLUSION

The created CAD model has shown that the prototype is a viable design for a SAMM mechanism. It has been shown with this prototype that a SAMM mechanism can be compact, cheap, and easy to assemble. The prototype presented provides a scalable design that can be easily adapted to accommodate extra DOF manipulation modules. In the ratchet mechanism it has been found that specific geometric conditions must be present to achieve an effective power transmission from the motor to the input shaft. Further research is being conducted to quantify the prototype limitations and capabilities.

5. REFERENCE

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