One Motor, Two Degrees of Freedom Through Dynamic Response Switching

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***Abstract*—To minimize weight and cost, it is sometimes desirable to power multiple functions with a single actuator. In this letter, we present a new mechanism for powering two degrees of freedom with a single motor. We introduce a method, termed dynamic response switching (DRS), in which the actuator can drive either of two outputs, forward or backward. Switching is accomplished by briefly dropping the speed below a threshold at a particular orientation. Hence, a wide range of speeds above the threshold is available for both degrees of freedom. We demonstrate the performance available with this device in a proof-of-concept prototype.**

***Index Terms*—Underactuated robots, mechanism design of mobile robots.**

I. INTRODUCTION

IN VARIOUS robotic applications, it is desirable to minimize weight and cost by controlling multiple degrees of freedom with a single actuator. Examples of such underactuated systems include a novel hinged rotorcraft [1] for which varying the torque of a motor creates the necessary thrust, pitch, and roll forces and torques for stable flight. Varying torques in a single motor of a running robot allows not only forward and backward motion, but also clockwise and counter-clockwise turning [2]. Other related examples include under-actuated acrobots [3] and systems like rotorcraft for which the number degrees of freedom in task space can be greater than the number of actuators. In robotic hands also, the need to reduce weight, complexity, and cost leads to underactuated designs with fewer actuators than degrees of freedom [4]. A variation on underactuation is seen in the Barrett hand, in which both of the two finger joints are driven by the motor until each individually hits a preset torque threshold [5]. Another variation uses a single degree of freedom to set the position of one output at one of a few predetermined locations, and then control the motion of the second output [6].

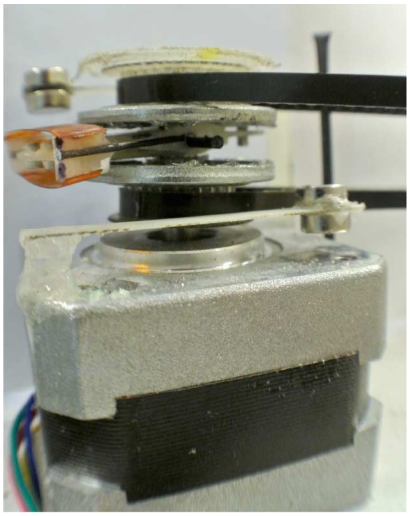

Fig. 1. A stepper motor outfitted with a DRS system which allows the motor to control two outputs (two black timing belts). See Fig. 2 and 3 for schematics.

Other systems use an active clutch to essentially “multiplex” a single actuator among multiple degrees of freedom. Examples include commercial desktop printers that use solenoids to switch the output of a single motor [7] and the popular Armatron toy, in which a single motor is coupled to a shaft with manually controlled clutches to power five degrees of freedom [8]. Brakes also can be used to “lock up” certain degrees of freedom on demand, as in the SRI/Meka/Stanford ARM-H hand [9]. However, these solutions require an extra control signal and an active device to achieve their capabilities.

Still another class of solution includes centrifugal clutches and brakes as found in seat belt retractors and various kinds of industrial equipment [10]. These require no additional control signal or power. However, they engage only at certain speeds so that if used to control two degrees of freedom, one output would be constrained to low speed regimes, the other to high.

In this letter, we introduce a concept, termed dynamic response switching, or DRS, because a switch is commanded based on the dynamic response of a switching element. A prototype using DRS (Fig. 1) transfers torque from the motor to either one of two outputs, at any of a wide range of motor angular velocities, both positive and negative. The torque is transferred with a bi-stable magnetic clutch (Fig. 2). In the up position, the magnetic pin in the clutch is attracted to and engages the steel teeth of Output 1 (Fig. 3, *Top*). The clutch is moved into the down position when contacted by the upper switching element, a cantilever beam with a magnetic tip which is free to oscillate (Fig. 3, *Bottom*). This oscillation is caused by the forcing magnets as they pass the switching element. The forcing magnets are rigidly attached to the drive shaft and located inside the clutch. If the motor speed is slow as the forcing magnets pass the switching element (low forcing frequency), the amplitude of response of the switching element is large, and the switching element contacts the clutch to cause a switch.

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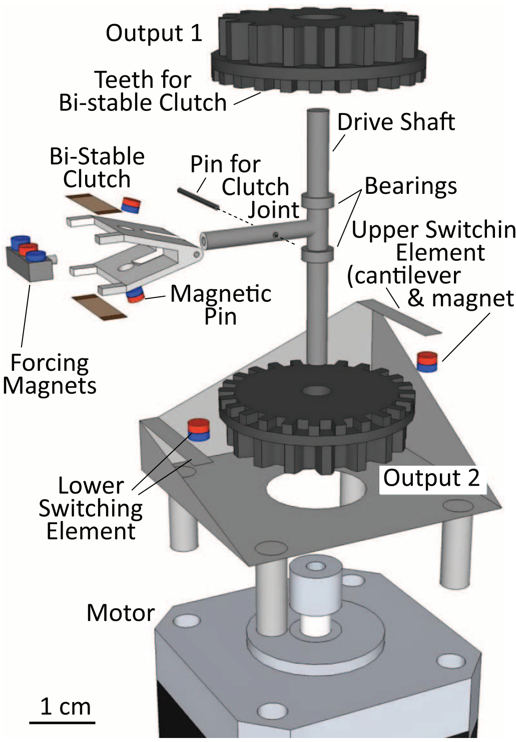

Fig. 2. Explosion view of the DRS prototype.

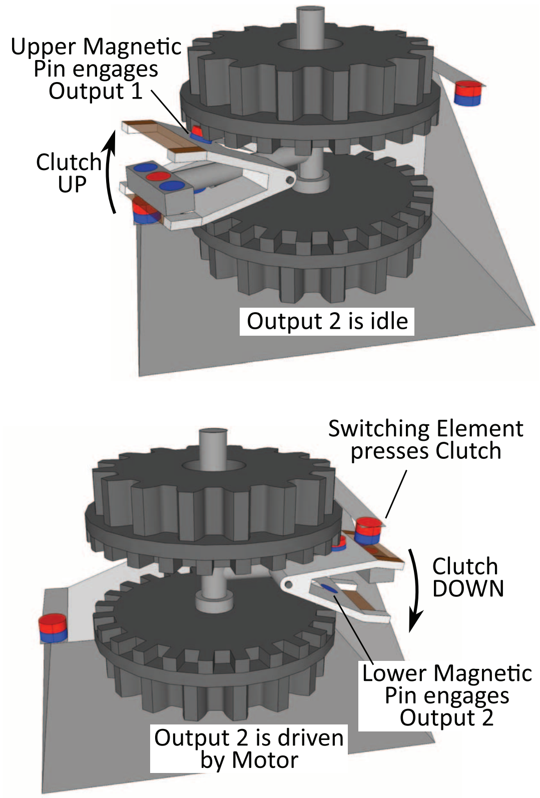

Fig. 3. Working principle of the DRS prototype. *Top*: When the bi-stable clutch is up, the magnetic pin engages the lower steel teeth of Output 1 and transfers motor torque to Output 1. *Bottom*: When the forcing magnets (rigidly connected to the drive shaft) are passed slowly by a switching element, they force a large amplitude response in the switching element, which in turn contacts the clutch. The clutch moves down, and Output 2 is driven.

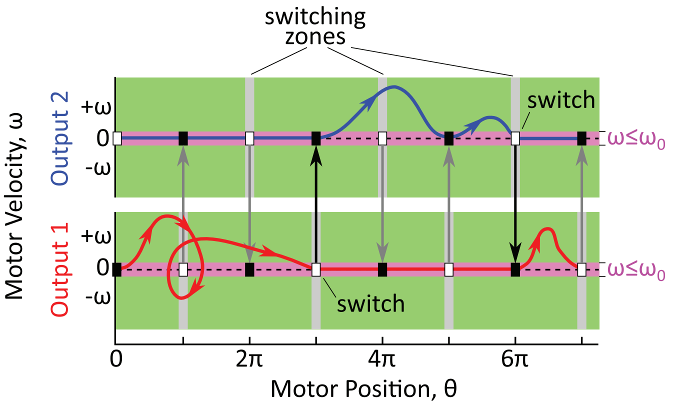

Fig. 4. A DRS system can control two outputs, one at a time. First, the motor drives Output 1 (*bottom, red*), fast and slow, forward and backward. Only when $\omega \leq \omega_0$ and the motor position aligns with a switching zone, does a switch occur. After switching, the motor drives Output 2 (*top, blue*).

In the following sections, we first describe the concept of DRS. We then give the details of the proof-of-concept prototype DRS system. Next we introduce a simple model to inform the design of systems based on the concept. We present results of an experimental model validation, and demonstrate how the DRS system can allow a single motor to sketch a picture using two degrees of freedom (similar to a plotter). We finish with discussion, conclusions, and future work.

II. DYNAMIC RESPONSE SWITCHING CONCEPT

A DRS system is able to control two outputs, one at a time, at any speed from stopped to the maximum allowed by the motor in either direction (Fig. 4). Switching only occurs when *both* the angular speed, ω, is less than or equal to a critical speed, ω_0, *and* the motor position is in a switching zone. Because both of these conditions must be satisfied to switch, any speed can be commanded when outside of a switching zone without triggering a switch.

The DRS system switches only at low angular velocity because the component that causes switches is a second order mass-spring-damper that is forced at a frequency determined by the angular speed of the motor. The amplitude of the response of the switching element is large at low forcing frequencies (Fig. 5, *top*). Any amplitude of response larger than a critical amplitude, A_0, causes a switch.

Further, the DRS system only switches in the switching zone because the forcing only occurs in these locations. A conceptual drawing of the DRS system shows why switching only occurs at low speeds and in certain locations (Fig. 5, *middle, bottom*). The switching element has a magnet for its mass. The forcing magnets are attached to the output shaft of the motor, and thus pass by stationary switching elements as the motor spins. As the forcing magnets pass by, the switching element oscillates. If the speed of the motor is low, this oscillation will be larger than A_0, and the switching element will contact the clutch. The clutch will be switched into the position away from the switching element (if the clutch is already in this position, nothing happens). If the speed of the motor is high, the oscillation of the switching element will be small, and the switching element will

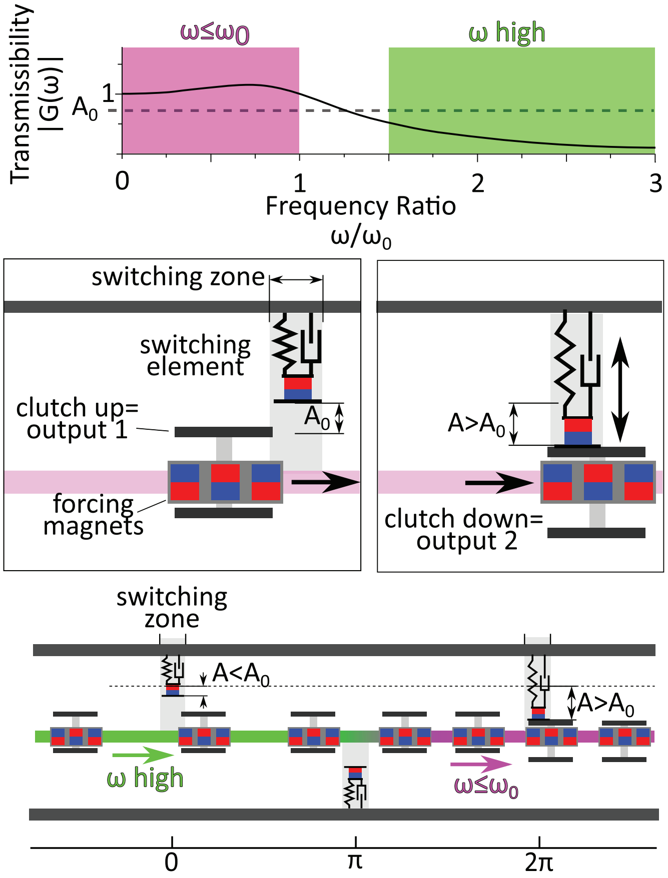

Fig. 5. *Top*: At low forcing frequencies, the amplitude of the response of the switching system is larger than A_0, the amplitude required for switching. *Middle*: The switching element oscillates as the three forcing magnets pass. If the amplitude exceeds A_0, the switching element contacts the clutch, switching it from up (transferring torque from the motor to output 1) to down (output 2). *Bottom*: As the motor turns, the forcing magnets move past switching elements. When ω is high, the switching element passes through a switching zone with only a small amplitude of response. Outside of switching zones, even when $\omega \leq \omega_0$, no switching occurs. However, when $\omega \leq \omega_0$ inside a switching zone, the amplitude of response, A, is greater than A_0, and a switch occurs.

not contact the clutch. In this manner, switches are only commanded when the motor speed is low *and* the forcing magnets are in a switching zone.

The details of how the clutch changes the motor torque from output 1 to output 2 are found in Sec. III-3.

III. IMPLEMENTATION

The four key components of the DRS system are the switching elements, the forcing magnets, the bi-stable clutch, and the lockable outputs. In the presented prototype, a stepper motor is chosen because it allows precise control of motor speed at different locations in a given revolution.

1) Switching Elements: To make the second order switching elements, we use cantilever beams that are rigidly fixed to the motor body (Figs. 2, 3). They have a 10:1 aspect ratio (wider than tall), such that while bending, the tip of the each beam moves vertically. The stiffness of the beam and mass of the magnet are chosen such that the resonant peak is at a frequency that is between the desired slow switching frequency and moderate to fast standard operating frequency (Figs. 5, *Top*). Damping is added to prevent vibrations from continuing long after the forcing magnets have passed.

2) Forcing Magnets: The forcing magnets provide the force to cause each switching element to oscillate. In the current implementation, there is a single set of three magnets. They are mounted to a beam that is rigidly attached to the drive shaft and extends through the center of the bi-stable clutch, between the prongs of the clutch (but not in contact with the clutch) (Figs. 2, 3). The first magnet is repulsive to the switching element magnet, the second attractive, and the third repulsive. When the set of forcing magnets passes near the switching element magnet, the cantilever magnet is initially repulsed, then attracted, then repulsed again. The frequency, ω_a, of this 1.5 periods of forcing is simply the magnet spacing, $x_2 - x_1$, divided by the linear velocity of the magnet on the switching element, v_0:

$$\omega_a = \frac{x_2 - x_1}{v_0}. \tag{1}$$

3) Bi-Stable Clutch: The bi-stable clutch is a "V"-shaped device that is connected to the motor shaft via a pin joint (Figs. 2, 3). This joint allows the clutch to rotate such that the tip is free to move vertically, but allows the motor to apply torque through the clutch. A magnetic pin engages with the steel teeth of one of the lockable outputs at a time. Due to the magnet, the clutch is bi-stable: it snaps towards the closer output.

The bi-stable clutch has one prong above the forcing magnets and one prong below them. If the clutch is up, and the upper switching element has a large amplitude of response, it presses the bi-stable clutch and causes it to switch to the down position. Note that if the upper switching element presses the clutch again (while the clutch is down), the clutch does not move.

A. Lockable Outputs

Attached to the drive shaft with a bearing, each of the two lockable outputs is a gear that is free to spin with respect to the drive shaft (Figs. 2, 3). The gears are able to drive timing belts or other gears, depending on the desired output. On the surface of each lockable output facing the bi-stable clutch are a second set of geared teeth. These teeth are able to mesh with the magnetic pin of the bi-stable clutch. Because the bi-stable clutch cannot rotate with respect to the drive shaft, when the pin of the clutch is engaged with the teeth of an output, the torque from the motor is transferred to that output. Note that in Fig. 1, the magnetic pin is on the opposite side of the pin joint as the clutch, meaning that when the clutch is up, the pin is down. The pin is drawn on the same side as the clutch in Fig. 2 and 3 for clarity. Either design is functional.

B. Fabrication

The implementation of the DRS system is a proof of concept prototype, and is therefore constructed from prototyping materials (Fig. 1). The lockable outputs are acrylic machined with a CO_2 laser. The motor has a 1.8 degree step size and is driven

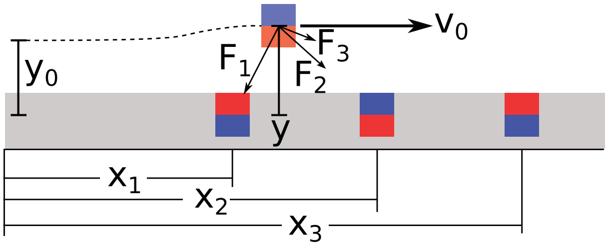

Fig. 6. Diagram showing parameters used in the model.

by a Big Easy stepper motor driver controlled by an Arduino Uno. The switching cantilevers are 0.75 mm thick, 5 mm wide, 30 mm long fiberglass. The mass of the magnet at the end of the cantilever is 2 g. Damping is added with CONFOR^{TM} open-cell polyurethane slow-recovery foam. The bi-stable clutch is also fiberglass, with a 50 micrometer thick polyamide film in the area where the switching elements make contact to prevent catching. The rotating magnets are mounted to a rigid fiberglass cantilever that is rigidly attached to the motor shaft via a press fit through-hole in the cantilever into which the drive shaft fits.

IV. MODEL

A simple model of DRS can be constructed to help inform the design of systems utilizing the concept. The model assumes the forcing of the single magnet at the tip of the switching element is caused by the three rotating magnets, one repulsive, one attractive, and then one repulsive (Fig. 6). While in reality the forcing magnets move in a circular path past the switching element, for this model, the switching element moves, on a linear path. The magnet on the switching cantilever is considered to have a constant x velocity when the motor is spinning at a fixed angular velocity.

The cantilever is modeled as a simple fixed beam with a force applied to its tip,

$$F_{beam} = \frac{3(y_0 - y)EI}{L^3}, \tag{2}$$

where y is the current position of the tip in the vertical direction, y_0 is the initial position, E is the elastic modulus of the beam, I is the second moment of inertia, and L is the length. Further, all magnets are considered small enough to be modeled as magnetic poles, or point forces. Therefore the force, F_i, between the moving magnet and the ith fixed magnet can be approximated by the classical magnetic force equation,

$$F_i = \frac{\mu q_{mm} q_{mi}}{4\pi r^2}, \tag{3}$$

where μ is the permeability of the air between the magnets in newtons per ampere squared, q_{mm} and q_{mi} are the magnitudes of the moving and the ith fixed magnetic poles in ampere-meters, and r is the distance between the magnets in meters. Finally, damping is added to the model, simply modeled as viscous damping with a damping coefficient, b:

$$F_{damp} = -b\dot{y}. \tag{4}$$

The force on the moving magnet is the sum of the forces from the cantilever, F_{beam}, from the fixed magnets, F_i, and from damping, F_{damp}. The acceleration in y is therefore:

$$\ddot{y} = \frac{1}{m}\left(F_{beam} + \sum_{i=1}^{3} F_i + F_{damp}\right). \tag{5}$$

Letting x_i represent the distance to the ith fixed magnet and v_0 represent the constant x velocity, and assuming all magnetic poles have equal magnitude, Eq. (5) can be rewritten as:

$$\begin{aligned} \ddot{y} = \frac{1}{m}\Bigg(&\frac{3(y_0 - y)EI}{L^3} + \\ &\frac{\mu q^2}{4\pi}\sum_{i=1}^{3}\frac{g(i)}{((v_0 t - x_i)^2 + y^2)^{3/2}} - b\dot{y}\Bigg) \\ where: \; & g(i) = 1 \, for \, repulsive \, magnets \\ & g(i) = -1 \, for \, attractive \, magnets. \end{aligned} \tag{6}$$

This differential equation can be solved to determine the amplitude of response (See Sec. V-A3). The model is helpful for determining the physical parameters of a DRS system given certain design goals. For instance, if the desired driving motor speed is known, the cantilevers and rotating magnets can be designed to assure the magnitude of response is small at this speed.

V. RESULTS

Three sets of tests were conducted. The first test helps validate the model, the second shows the performance of the DRS in terms of maximum switching rate, the third implements the DRS concept on a single stepper motor driving two degrees of freedom for creating a 2-D sketch.

A. Model Validation

In order to validate the model, a test setup that represents a simplified version of the key components of the DRS system was constructed.

1) Test Setup: The setup comprises a motor, a switching cantilever, and rotating magnets (Fig. 7). The setup is much larger than the version of the DRS prototype in order to more easily gather data. The switching cantilever is 5 cm long. It is constructed of 0.5 mm thick, 8 mm wide spring steel. The separation between the switching cantilever and the rotating magnets is 2 cm. A high-speed camera is positioned to film the motion of the tip of the switching cantilever. A retro-reflective marker is attached to the tip of the cantilever, and video is recorded at 400 fps. The motor is run at a constant angular velocity for each test, and 8 different angular velocities are recorded. Video is analyzed in MATLAB to track the position of the tip of the switching cantilever.

2) Experimental Frequency Response of the Switching Cantilever: As the forcing magnets pass under the switching element, a forced response followed by a free response is seen in the vertical motion of the switching element (Fig. 8, *left*). At a high angular velocity of the motor (2.2 rad/s), the relative velocity of the switching element and the fixed magnets

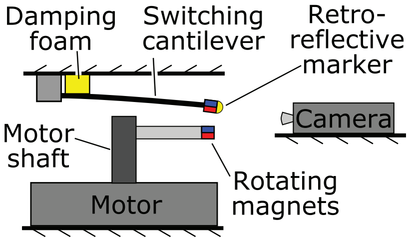

Fig. 7. Drawing of the test setup for model validation.

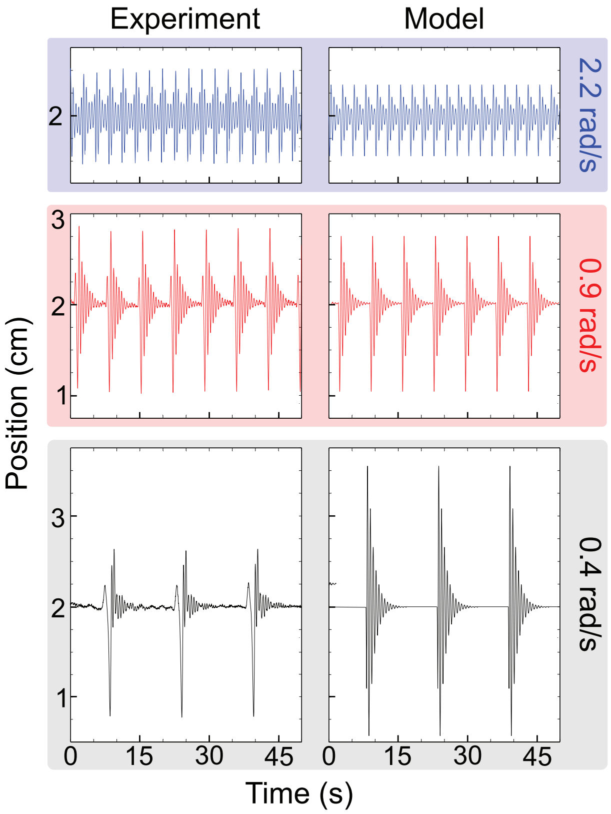

Fig. 8. *Left*: Experimental results showing the response of the switching cantilever at three different driving frequencies of the motor. *Right*: Results from the model showing the response at the same frequencies.

is high, creating a large ω_a. The amplitude of the response of the switching element in the direction of the rotating magnets (toward $y = 0$) is therefore small, only 0.5 cm (Fig. 8, *left, top*). As the angular velocity is decreased to 0.9 rad/s, the amplitude increases to 1 cm (Fig. 8, *left, middle*). A further decrease in angular velocity to 0.4 rad/s increases the amplitude to 1.25 cm (Fig. 8, *left, bottom*). Any slower angular velocity of the motor results in an amplitude of the response large enough to cause the switching element to contact the forcing magnets and cause a switch.

When these amplitudes, along with results from 5 other motor speeds, are plotted against the forcing frequency, ω_a, an experimental amplitude response plot is created (Fig. 9). The plot clearly shows the drop off in amplitude above roughly 2 rad/s. Note the upturn in the amplitude at low frequencies, due to the non-linearity of the magnetic force. The maximum amplitude is 2 cm, since contact with the rotating magnet is made at this displacement.

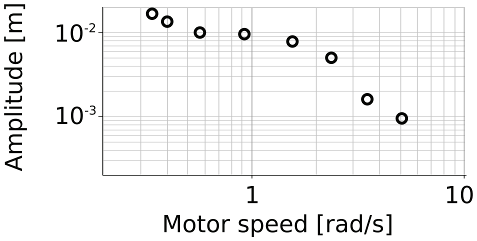

Fig. 9. Amplitude response of the switching cantilever.

TABLE I
PERFORMANCE SPECIFICATIONS FOR PROOF OF CONCEPT PROTOTYPE

Metric	Value	Notes
Min switch time	300 ms	Time to switch from Up/Down to Right/Left or vice versa.
Max switch rate	0.4 Hz	Motor must rotate to opposite switching cantilever for each switch.
Max output speed	6 Hz	Tested while supplying 1 kg-cm of torque.
Max output torque	1.5 kg-cm	Currently limited by timing belt slip.

3) Comparison to the Model: The measured values for the test setup are put into the model, and the output for each of the three motor angular velocities can be compared to the experimental results (Fig. 8, *right*). The parameters of the model are all measured from the system, except the damping ratio, b, which is fit to the results for a single motor speed, and left unchanged for the other data. The amplitude in the direction of the magnets (toward $y = 0$) is predicted fairly well, however due to errors in measured parameters, there are slight differences. The largest qualitative difference is the considerable asymmetry seen in the data, especially at low speed. This is due to the experimental setup, which had damping foam on one side of the cantilever (Fig. 7). Large motions away from the rotating magnets resulted in very large damping forces, hence the asymmetric shape. However, because the model is useful for predicting amplitude for switching (in the direction toward the magnets) based on motor speed, this unmodeled effect is not critical.

B. DRS Prototype Performance

While this implementation is a proof-of-concept, it is useful to characterize the capabilities of the device. The results of the tests conducted are shown in Table I.

C. 2-D Sketch With One Motor

The DRS system is implemented onto a single stepper motor as shown in Fig. 1. Each of the outputs is connected via timing belts to the drawing wheels of an Etch-A-Sketch 2-D drawing device. Note that this device was chosen for use as a simple demonstration of the ability to control 2 degrees of freedom, rather than as a practical application.

An Arduino sent only speed and direction commands to a single stepper motor, and both wheels of the device were controlled. The letters “BDML,” for Biomimetic and Dextrous

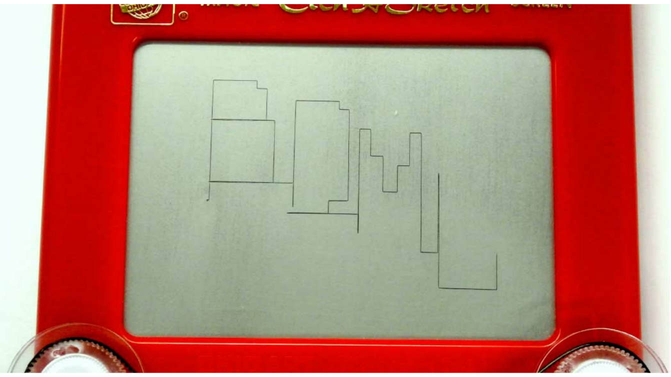

Fig. 10. A single motor implemented with a DRS system is capable of turning 2 knobs and drawing a 2D sketch.

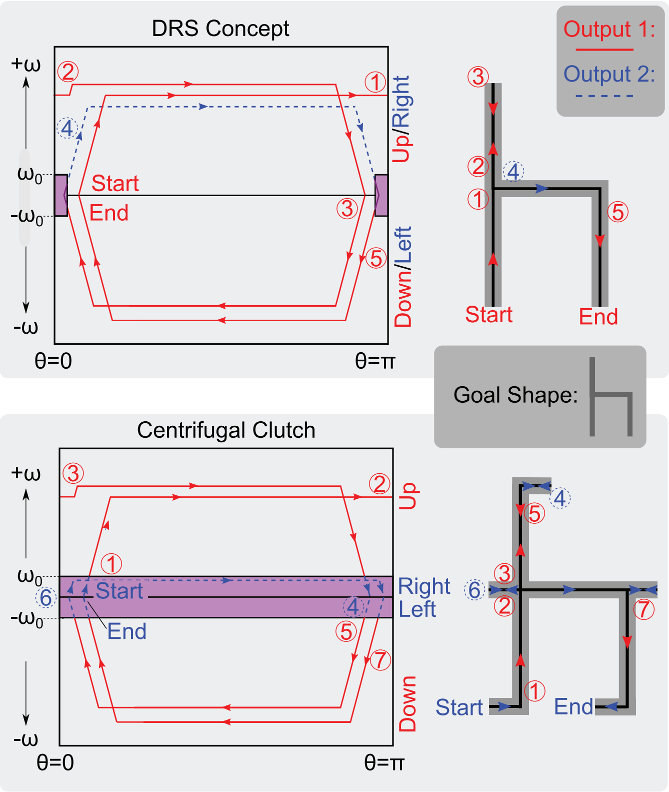

Fig. 11. A schematic illustration of drawing the letter “h” with the DRS concept (*top*) versus with a device such as a centrifugal clutch (*bottom*). At left is shown the state of the outputs in phase space, and at right the resulting drawing. Numbers indicate the order of operations.

Manipulation Lab, were drawn numerous times without error, requiring 31 output switches each time to change from up/down to right/left and vice versa (Fig. 10).

In order to help visualize the capabilities of the DRS concept in a drawing task (here a letter “h”), it is possible to show the two outputs in phase space (Fig. 11, *top*; Output 1 in solid red, Output 2 in dashed blue). Both outputs can be driven at any motor angular velocity, ω, above the critical switching angular velocity, ω_0, since no switching occurs in this case. This is in contrast to a simple centrifugal clutch (Fig. 11, *bottom*), in which the motor speed must remain below ω_0. This results in poor actuator efficiency while driving Output 2. Also, the DRS system allows both outputs to change direction without switching the output, as long as the direction change does not occur near $\theta = 0, 2\pi$ (the small rectangles at $\theta = 0, 2\pi$ represent switching zones in phase space). The centrifugal clutch does not have this property, and creates a letter “h” with multiple extraneous lines (any change in direction of Output 1 results in a brief driving of Output 2).

VI. DISCUSSION

While the DRS concept increases the capabilities of a single motor by allowing control of two outputs, it has a number of limitations. For instance, the motor can only drive one output at a time. For certain applications, this is acceptable. An example is an airplane that flies then perches and climbs in order to do inspection of large structures such as dams. A single powerful actuator could spin the propeller while flying, then once perched on a wall, drive climbing legs or wheels. For applications where it is desirable for both motors to be active at the same time, fast dithering can offer an approximation to two fully independent motors. In the example of the 2-D drawing, two motors could draw a stair-step diagonal line. Of course, with dithering, the total power that can be provided to the two outputs is half of what two motors could provide. However, the torque would be the same.

A second limitation is that switching must occur at a specific orientation of the motor. For highly geared systems, this is not a significant issue because a full rotation of the motor results in only a small change in the position of the output. However, for systems with very low gearing, an active clutch system that is able to switch at any orientation of the motor could be more appropriate.

Further, the idle output is not actively locked in the DRS concept. This presents a problem when both 1) using a low gear ratio, such that the gear train is backdrivable, and 2) there could be external torques applied to the output. While not implemented here, a simple locking pin could be added to the clutch that locks the idle output to the motor body when the clutch is engaged with the other output. For any case with a high gear-ratio (non-backdrivable) or with outputs that will not experience large external torques, the current implementation is acceptable.

Another limitation is the size of the switching system. Currently it is a significant fraction of the total motor size, making the argument of space savings somewhat dubious. However, this proof of concept prototype is hand built with low-strength prototyping materials and could be significantly scaled down. If the same output speeds were desired, scaling would require the smaller switching cantilevers to be dynamically matched to the current ones. Scaling of the rest of the system would be straightforward, with the largest challenge arising from tighter tolerances.

Finally, there is a question of robustness to external disturbances. The vibration of the switching elements could be a concern for certain applications, however can be mitigated with damping. Simulation and tests show the DRS concept works with damping from $\zeta = 0.01$ to $\zeta = 1$; the only change is the frequency at which switching occurs (higher damping results in a lower switching frequency). A second type of disturbance is

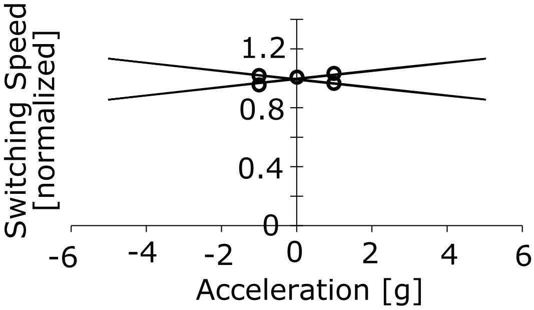

Fig. 12. With external acceleration, the switching speed of the two cantilevers is plotted (model = solid lines, data = circles). Switching speed is normalized to the speed required at 0g.

acceleration. However, because of the relatively high stiffness and low mass of the switching elements, the system is quite robust to accelerations. Fig. 12 shows the results of simulation and testing under various accelerations; the simulation predicts only a change in switching velocity of roughly 20% for up to $6g$. Experiments also show negligible change in switching speed for $\pm 1g$. Therefore, if large accelerations are expected, a window of switching speeds exists. For instance, if up to $3g$ in either direction is expected, switching could occur anywhere between 0.9 and 1.1 times the switching speed at $0g$. As a result, the lowest speed where a switch is guaranteed not to occur is 1.1 times higher than at no acceleration, and the motor must maintain a slightly higher speed through the switching zones.

VII. CONCLUSION AND FUTURE WORK

We have presented Dynamic Response Switching, which allows a single motor to control two degrees of freedom. A simple model predicts the amplitude of response given the physical characteristics of the system. Empirical results match the model, with minor differences due to asymmetric damping. A prototype illustrates the capability for a simple 2 DoF plotting demonstration using a single stepper motor. We have also discussed limitations of the approach and demonstrated its performance under different external accelerations.

The next step is to create a second generation system that fits within a much smaller footprint and is manufactured of stronger materials and at a higher resolution. Such a device could offer practical advantages in many robotic applications where cost, weight, and size are at a premium.

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