Spirobot: A Kinetic Art Piece and Study in Linkage Actuation For Robotic Armatures

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***Abstract*— Spirobot was initially conceived as an art piece to demonstrate the resulting geometric shapes created by objects spinning on the end of other spinning objects. This is primarily inspired by fire dancers who spin staves to create interesting and beautiful effects. As the project progressed the potential emerged for this to be possible low cost solution for building simple and controllable robotic armatures.**

I. INTRODUCTION

In the discipline known as staff spinning or staff manipulation there are two basic relationships between the spin of the staff and the spin of the arm. Antispin describes the staff spinning in the opposite direction as the arm driving it. Inspin describes the staff spinning in the same direction as the driving arm. The resulting geometries of these two simple relationships have characteristic differences that give a performer a range of expressive possibilities.

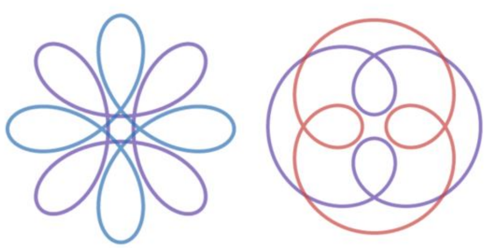

Fig. 1. 3 Prop Rotation to 1 Arm Rotation. Inspin on right, Antispin on left. Note that these patterns are composed of 2 separate closed curves, one generated by each side of the staff

The goal for this machine was to be able to show these patterns in a stable state and select which patterns to display. An effective implementation of this behavior needs to have a closed loop control system for the speed of the arm and staff. The Spirobot's control system as it is implemented today is instead designed to command set positions for each motor. The position control system is able to track quickly changing movements within a certain range and speed with good responsiveness. Responsive position control on this kind of system could be applied to the design and production of low cost controllable robot armatures.

II. MECHANICAL DESIGN

Spirobot is the product of an iterative design approach, there were four prototypes that each significantly improved on the last. The basic function of the machine is this: there is a main armature driven directly by a motor, on this

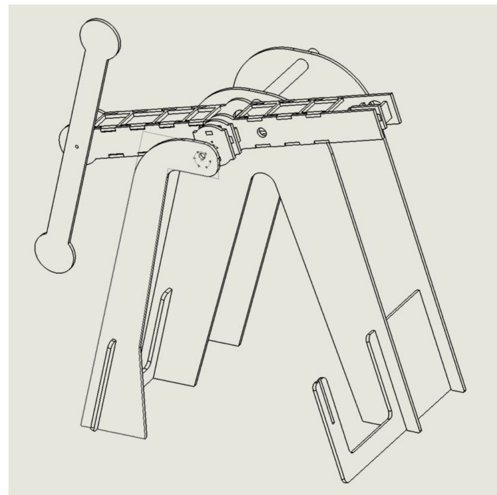

Fig. 2. Mechanical Design, motors and belts not pictured

spinning armature is a second motor on one end which drives a belt that turns the staff on the other end. Using a belt driven system allowed for the second motor to act as a counterbalance to the staff, resulting in a well balanced system with a moment of inertia very close to the center of rotation of the main arm. Determining the best location to place the motor is a reasonably simple problem. The simplified model shown in figure three can be effectively used to calculate the ideal motor location to balance the main armature.

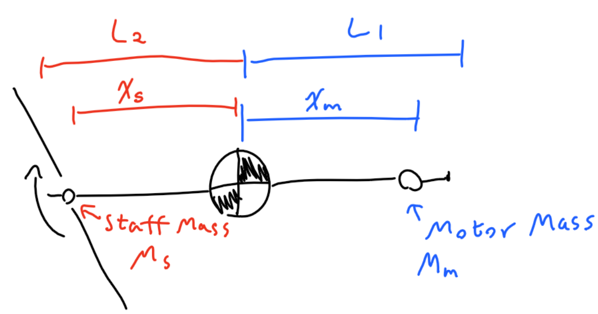

Fig. 3. Simple Model for Moment Calculation

In this model L_2 and S are known distances from the point of rotation, these are design choices. The distance between L_2 and M is a design choice as well. This leaves M as the design consideration that needs to be solved. Additionally, the density ρ of our stick model needs to be known. For simplicity the spinning staff will be treated as a point mass, this will result in a good approximation of the average moment it applies on the center of rotation. The moments applied on the center by the left and right side must be equal, therefore

$$x_s M_s + \int_0^{L_2} \rho x dx = x_m M_m + \int_0^{L_1} \rho x dx$$

Since the left hand side is made up of known values, it will be referred to from now on as the constant K. An additional parameter defined as $W = L_1 - x_m$ will be needed. W is simply the amount of material on the main armature that goes past the motor. As stated earlier, this is a design choice. The solution that balances the system will then be one of the roots of the polynomial

$$\frac{\rho}{2}(L_2)^2 + M_m L_2 - (W M_m + K) = 0$$

namely:

$$L_2 = \frac{-M_m + \sqrt{M_m^2 - 4\frac{\rho}{2}(-(W M_m + K)}}{\rho}$$

Some quick estimations were made to plug the real world system into this formula. Over time adjustments had to be made as different materials were used to build new versions of the machine. Additionally, the motors currently on the system are the third that have been tried, the masses of the different motors differ with enough significance to affect the balance of the arm. The first two prototypes were made from of MDF, the third was made from birch plywood, and the current iteration is a mix of birch with a number of acrylic components.

A. *Mechanical System Challenges*

Outside of the CAD design, one of the surprising difficulties of this project had to do with splicing together loops of GT2 timing belt. There was a number of failed attempts before a solid enough process was determined. The belt was cut such that it had corresponding diagonal ends with teeth that line up, they were then clamped down to a table, and joined at the ends with a small dab of hot glue placed on the smooth back of splice. This method proved to be reasonably easy to complete quickly, which is important because these spliced belts tend to break under use. For future builds it would be a good idea to obtain a custom length timing belt loop or determine if the design can be adjusted to accommodate a standard length belt loop.

Prototype number three was cut primarily from Birch plywood with all the points of rotation having metal turning against wood. The result of this is a rather unpleasant and loud squeaky noise. The friction generated also had a notable impact on the performance of the motors. In the current iteration, all points of contact with metal are made from acrylic. Acrylic bushings were designed and pressure fit into a new armature modified to receive these parts.

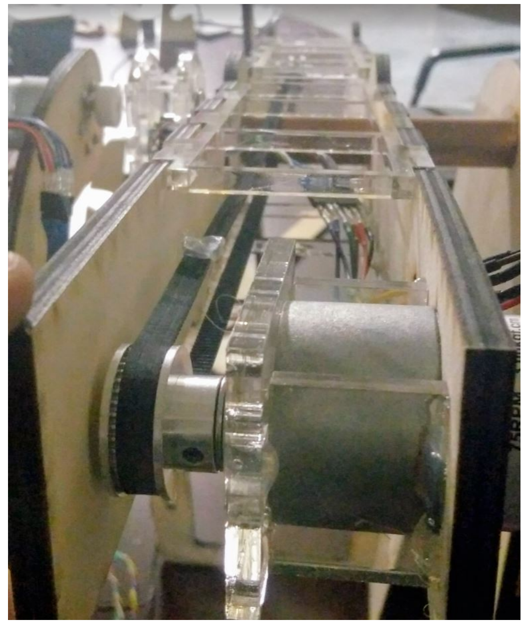

Fig. 4. Spliced GT2 Belt, hot glue glob visible

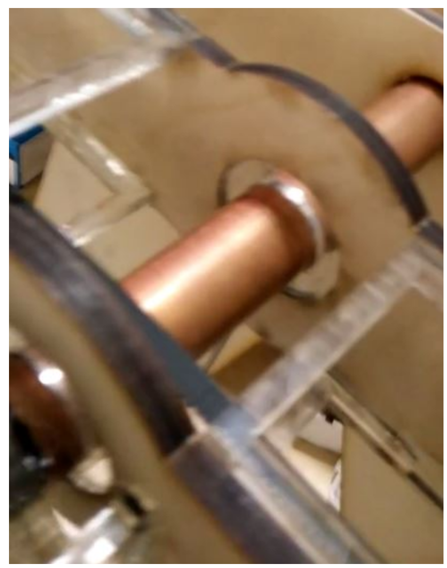

Fig. 5. Acrylic Bushings for smooth operation with no squeak

III. ELECTRICAL COMPONENTS AND DESIGN

The two motors used in the machine are 12V 70rpm motors with hall effect quadrature encoders mounted on the back. The motor on the spinning arm is wired through a slip ring that feeds the connection through the hollow tube around which the main arm rotates. The slip ring is a critical component without which the wires would very quickly wind up around the center axis and cause havoc to the machine. Each motor has six wires coming out of it. Two are needed to drive the motor, two are needed to power the encoder and the last two are the encoder channels. All these wires plug into the outside of a box built to house the main microcontroller and the separate motor driver board. This modular plug and play set up allows for easy testing and quick set up/take down. Two other encoders are used as inputs to control the system. These are each housed in their own boxes and also connect to the outside of the main control box.

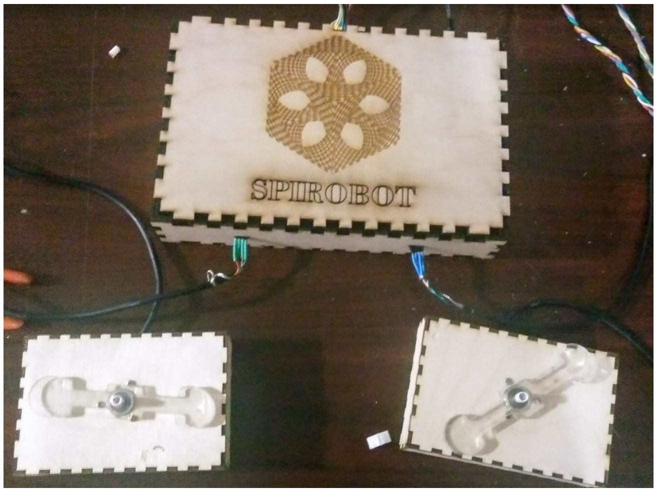

Fig. 6. Internal wiring

The main microcontroller used in this system is the Cypress PSOC 5LP which is a powerful system on a chip with many tools that make aspects of the software design take considerably less effort than with more standard controller. The PSOC platform includes built in quadrature decoders with an API that provides straightforward access to the measured count which can then be used to determine angular distance traveled, speed, and direction. Furthermore, internal electronics on the chip allow for the use of signal channels that would normally require pull up resistors. This can be accomplished by simply changing the settings for the pin through their software. This makes the controller route through an internal pull up resistors. In order to drive the motors the system uses an external H-Bridge board controlled with two digital inputs and a PWM channel from the PSOC. This allows for effective control of magnitude and direction of current passing through a motor with an adequate amount of resolution for the demands of the product.

A. *Electrical System Challenges*

There are some aspects of the internal wiring that could be made more robust. Every encoder needs to access 5V and GND and the addition of a permanent screw terminal power distribution solution would make the control box less sensitive to physical shock. Currently the on board breadboard is being used to distribute these power channels. This solution comes with major drawbacks, primarily, the problem is that wires can somewhat easily come out of the breadboard resulting in a loss of signal from the encoders which are needed to run the control system. That being said, this has been a workable short term solution while the project continues to be refined. In order to make this system as modular as possible a lot of soldering was done connecting wires to headers and pins. Unfortunately much of this soldering was not done very well and several connections have broken. Re-soldering these broken connections would require taking out a lot of wiring. Fortunately all the joints that have broken are still able to be used like plug jumpers, if the heat shrink covered wire is pushed back on the pin, it will still function effectively, but with a sizable loss of robustness.

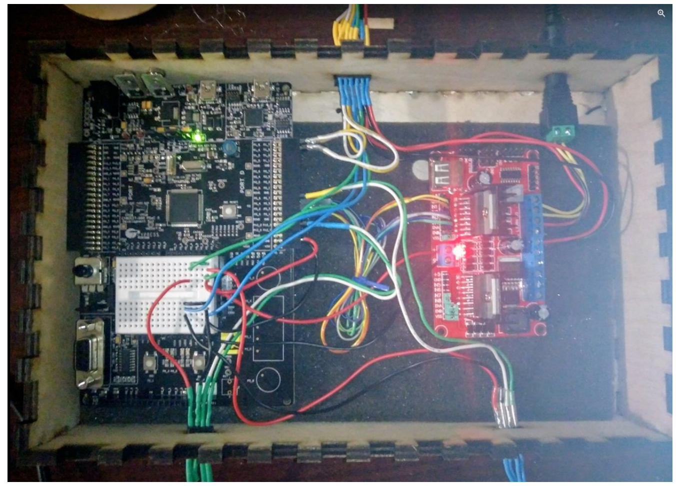

Fig. 7. Inputs and outputs from ”Brain” box

With 12 Wires coming out of the system into the controller, exterior wire management is a challenge, the currently implemented strategy has been to tightly wind the bundles of six into one single plug cable with header pins on both sides. One end plugs into the motor and the other into the main control box. To manage the potential wiring mess with these long stiff cables, the twisted wires are routed through a specific path of holes near the bottom of the stand. This keeps the wires out of the way of the moving parts but lacks aesthetic appeal. Bundles of twisted wires are not a part of the intended look of the project. As refinement continues, they will be covered in black heat-shrink to both hide them and ensure that no stray object catching something can pull a wire from the twist.

IV. CONTROL SYSTEM

The control system implemented on Spirobot is a simple PID control loop commanding the positions of the two motors. The commanded reference is generated from the input encoders and the feedback is received from the encoders mounted on the back of the drive motors. The design of the control system was done using an iterative tuning process rather than mathematical methods such as root locus. This was the only viable option due to the lack of a dynamic model of the overall system. Such a model could be used to simulate the effects of different control strategies without needing to load them onto the machine. The process used to design the control system instead required implementation on the real system. The system would them be observed for the purpose of determining what gain value test points effectively resulted in the desired behavior. The first control system design attempt used only a simple proportional gain value. This did a reasonable job controlling the motor on its own but there were significant drawbacks with overshoot and oscillation around the commanded reference point. After testing several values, the proportional gain was set to 100. To improve this system, an integrator channel was added, creating a PI control loop. The integrator gain was tuned by progressively doubling the values until the system behaved erratically, from there the value was dropped by half and changed only slightly from that reference point until reaching a value of 0.05. The resulting controller did a decent job at reaching the commanded position. However, 30 seconds or so into operation, the motors became too hot to touch. It was determined that the cause of this issue was the high proportional gain value which was causing very small but powerful oscillations around the reference point. This meant that even though the motor shaft was remaining relatively still, the current draw of the motor was significant. After halving the proportional gain down to 50, the system no longer had the fast punchy reaction to input that it had with the higher proportional gain value. This meant the system could benefit greatly from a derivative channel, making it a true PID control loop. Fast reaction to large change is the main job for a derivative channel. The derivative gain was set to ten after undergoing a similar tuning process as the one used to determine the ideal integral gain, larger initial test values were used. The resulting control system reacted fast and could run for minutes without motors heating up. Longer term stress tests should be undertaken to determine if the system could be left idle for hours or days at a time.

A. *Control System Challenges*

Further into the testing, it was observed that spinning the reference control encoder fast and far in one direction would quickly cause the system to stop suddenly and change directions at full motor drive force. This broke a timing belt in one instance and broke an acrylic piece off the main arm drive platform in another. This turns out to have been caused by overflow in the 32 bit counters used for quadrature decoding. The input would command an ever increasing position until it rolls over to zero and the system reacts accordingly, with a massive spike error term accompanied by a hard turn in the opposite direction. This issue was addressed by subtracting a constant value from both the input counter and the motor counter as either one approached its limit. This strategy maintains the error term while ensuring that the counter values stay within a usable range.

V. FUTURE POSSIBILITIES

Spirobot should light up, there are currently plans to cover much of it in LEDs. The geometries within the motion of the staff are best shown with moving light. For the system as it is today the only practical way to mount lights on the staff end would be to individually fasten battery powered lights. However, were the second rotation axis hollow, then a low cost slip ring similar to the one on the main armature could be fastened on the end. This would allow for a much more intricate light set up with the potential to do interesting persistence of vision effects.

There are many places on the body which a two joint system like Spirobot could imitate based on orientation data from an IMU. Rather than commanding position with input encoders, the orientation of the IMU could generate the references commands for motor position. This level of interaction with a mechatronic system could provide an engaging user experience with the potential to expand the device into a game peripheral. Were this system mounted on wheels there could be many interesting possibilities including stiff robot sword fights or one player target hitting from a moving platform. The simplicity of the system and its controls means tha Spirobot variants could be mounted on or integrated into larger interactive art projects. The Spirobot system alone is a fun installation that will be set up at several juggling and fire spinning festivals in Summer 2017.

VI. ACKNOWLEDGMENTS

Thanks to Gabriel Elkaim for acting as Faculty Advisor for this project

Fig. 8. Complete Spirobot System