Project Number: P13029

JUMPING ROBOTIC TIGER

Trevor Crandell
Mechanical Engineering (EMEA)

Jeffery Manicone
Mechanical Engineering (EMEM)

Phil Brown
Mechanical Engineering (EMEM)

Sean Mosier
Mechanical Engineering (EMEM)

Andrew Pace
Mechanical Engineering (EMEM)

ABSTRACT

The tiger robot is a McKibben air muscle operated mechanical frame which is propelled in a jumping motion. The robot was built under the direction of Dr. Lamkin-Kennard and aided by the legacy data from previous McKibben air muscle powered robotics of past senior design teams. The tiger is meant to mimic the motion of a real tiger jumping through the air. The robot is tethered and is operated by a compressed air source and customized valves for high flow rate to the muscles. The exhaust air and the high flow rate valves are operated by pneumatic solenoid valves driven by an Arduino microcontroller with serial input for user interfacing. These valves are fired in order to emulate the contraction of separate muscle groups (e.g. hip, thigh, and calf). Not all customer requirements were met for this project. The most significant of our unmet requirements included a controlled landing and being self-contained. However, the robot met the main customer need of being able to jump its body length.

INTRODUCTION

This project is part of a series of biomechanical projects, supported by Dr. Lamkin-Kennard's research on McKibben air muscles. The original projects started with the development of artificial limbs, and have now grown to include biomimetic robots such as a biomimetic crab and ant. The tiger robot is meant to be a significant step forward as it is the first robot that has had to generate enough force in a short amount of time to propel a frame into the air in a jumping motion.

Figure 1: McKiben Air Muscle in a state of contraciton.

The McKibben air muscles were first developed in the 1950's by J.L. McKibben, these muscles are noted for their ability to mimic the nonlinear force profile of biological muscle tissue, as well as their large strength to weight ratio. These muscles are constructed of a section of elastic tubing surrounded by braided wire sheathing, clamped at both ends. When the tubing is pressurized it inflates and the sheathing around the muscle contracts, generating force and contraction within the muscle. These muscles only produce a force in one direction and therefore need another muscle or returning force to return the limb to its original position, unlike a pneumatic piston.

PROCESS

Accelerometer Testing

An accelerometer was used to determine which tube thicknesses provided the largest force and to verify the effects of increased orifice size. A 10 lb weight was hung from the bottom of the muscle. The accelerometer was placed on the top of the weight. Results show a sinusoidal acceleration profile with different magnitudes, depending on tube thickness and orifice size. Initially the goal was to extract a muscle force profile for use in a Matlab simulation. Knowing the weight moved and its acceleration, a dynamic analysis could be applied to find the force. Because of uncertainty surrounding where the data started and ended, these force profiles were unable to be obtained. However, looking at the magnitudes of the accelerometer data told us two important things. First, the largest orifice size provides the largest acceleration. Second, the largest tube thickness had the smallest acceleration and there was no notable difference between the middle and smallest thicknesses. However, the medium tube diameter handles the fatigue of repeated actuation better than the small tube diameter. Overall the results of this test determined the 3/8" orifice size and the 1/4" tube thickness used in the final design.
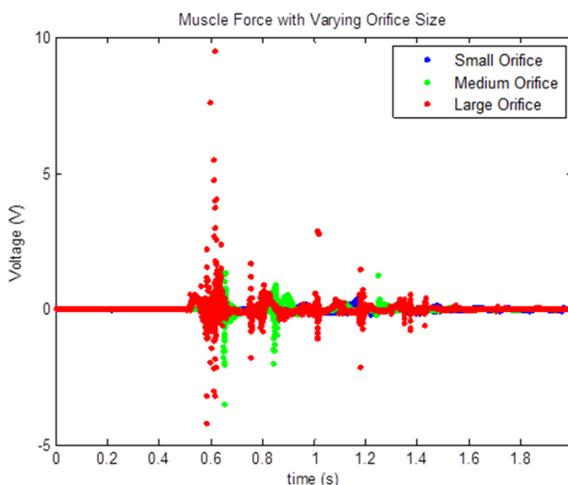

Figure 2: The plot above shows muscle testing with a 1/8" diameter orifice size.

Reduced Friction

After initial testing, friction was determined to be a potential problem. The initial design overlooked a few surfaces that were in contact that had large coefficients of friction. Specifically the contact surfaces between the rotating limbs, pins, and machined holes were found to be problematic. Nylon washers were added between the metal surfaces of the joints in order to reduce friction. Large amounts of friction were removed with the changes described above. These changes were made after an unsuccessful initial test. Friction was part of a series of problems being addressed in a hope to improve upon the initial design.

Theoretical Analysis

The tiger takeoff and free flight were modeled dynamically and animated in Matlab. While the modeled design did not end up being used as the final design, the simulation revealed several things that aided in the design of the tiger. The simulation revealed the need for a sequence of muscle group firings as opposed to all muscles actuating at once. When all muscles fire at once, the bottom muscle cannot overcome the reaction forces due to the upper two muscles. The simulation also revealed the need for hard stops at each joint to prevent over extending of each leg segment. Hard stops stop each leg segment at an optimal jump angle of about 45°.
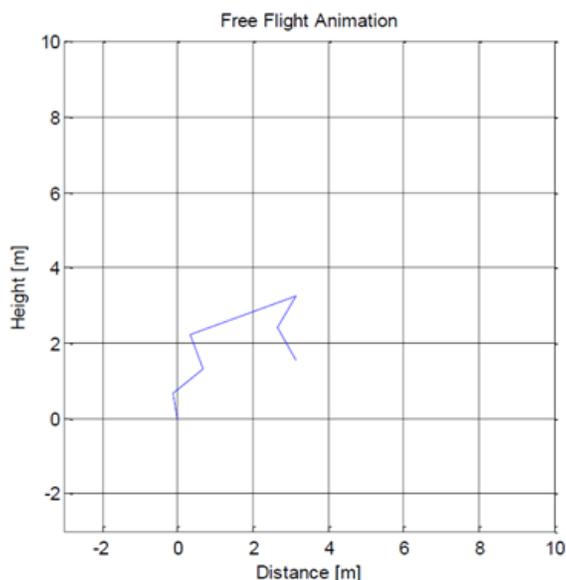
Figure 3: Screenshot of a mid-flight dynamic simulation in Matlab.

The goal of the simulation was to be able to input muscle forces, link lengths, initial starting positions, and masses of each link/body element, and have the simulation output the tiger's jump distance. However, due to the inability to collect reliable muscle force data, we were not able to input accurate muscle forces into the simulation. Furthermore, the simulation was started very early in MSD I. However, lessons learned from prototyping in MSD II drastically changed the tiger design from the design used in the simulation, rendering the simulation inaccurate. The simulation was modeling pulleys at each joint. However, testing at a later time revealed that an overhang design would allow us to harness the force from our muscles in simpler manor that accomplished our objectives. The lever design was determined to produce more force at a cost of leg displacement.

Air Supply

Early testing revealed the need for quick filling muscles to provide the large muscle accelerations needed for jumping. As shown in equation 1 below, flow rate is dependent on the cross sectional area of the path through which the air is flowing, and the velocity at which the air is flowing.

$$Q = vA \text{ --- (1)}$$

Testing supported this concept, showing that orifice size had a significant impact on muscle force. The initial tethered and untethered air supply source solutions were the RIT wall air supply and a paintball tank, respectively. However, both paintball tanks and wall air supply had limiting orifice sizes of 1/8 of an inch; much smaller than the limiting muscle orifice size of 3/8". As a result, the decision was made to use a tank as a pressure vessel with a large diameter outlet, so as not to impede the airflow.

A pressure vessel also allows for increased air speed, and therefore increased flow rate. The tank must be pressurized to a pressure greater than the desired muscle pressure to account for the pressure drop when the air is released into the muscles. This increased pressure causes increased air speed, as shown below in equation 2 Bernoulli's equation (neglecting elevation changes and assuming a Mach number less than .3).

$$\frac{v^2}{2} + \frac{P}{\rho} = constant \text{ --- (2)}$$

Due to safety concerns, muscle air pressure was limited to 60 psi. To ensure that the muscles were inflated at to this limit, a spreadsheet was developed to predict the pressure drop in the system when air was released from the tank to the muscles. These calculations were made by using the ideal gas law and assuming constant temperature, shown below in equation 3.

$$P_1 V_1 = P_2 V_2 \text{ --- (3)}$$

These predictions were verified in testing for various tank and muscle configurations. *Figure 5* below shows the accuracy of these predictions for one trial setup.

Component Design – Controls

An Arduino Mega 2560 microcontroller was used for this project due to its vast customization options, easy programming language, input and output capabilities, and its ability to be reused in future projects if necessary. The Mega2560 features ample digital I/O pins for solenoid firing. The robot requires 2 digital outputs to operate; one output to signal the firing of the pneumatic solenoids the other for exhaust. This board also uses a simple programming language and there are many open source examples of code which aided in the development of a graphical user interface (gui). The board was inherited from a previous project and left plenty of room for improvement for possible future additions.
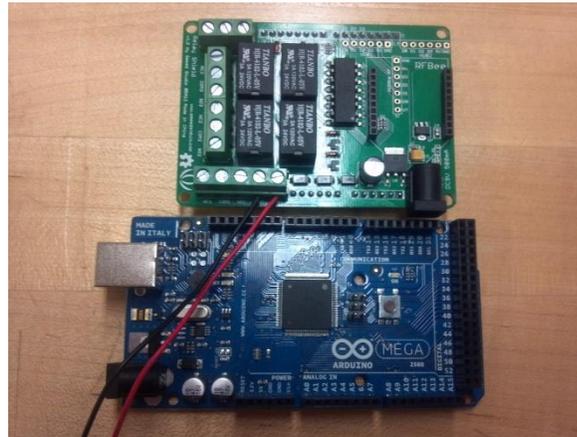

Figure 4: Picture showing the Arduino control board used along with the relay board. These controlled muscle firing timing.

Hardware selection for the final design used a relay circuit shield add-on for Arduino which adds four relays with protection circuits to the Arduino board itself. This circuit consists one of each of the following components: a diode, transistor, voltage regulator, resistor, and relay. This board was able to take the digital signal from the Arduino at low voltage and use an electromechanical switch to power the 24 volt relay. The control flow for the tiger robot has a delay between the firing of the two relays that controls the jumping motion of the two muscle groups of about 100 milliseconds.

Component Design – Tank and Airflow Network

Proof of the pressure vessel concept was done economically and quickly by creating a PVC pressure vessel with a ½" outlet. The PVC tank was operated at low pressure for safety (less than 30 psi). Upon testing with the PVC tank, it was immediately seen that muscle orifice size became the limiting factor in fill rate as the 'bottleneck' caused by the previous air supply concepts had been removed.
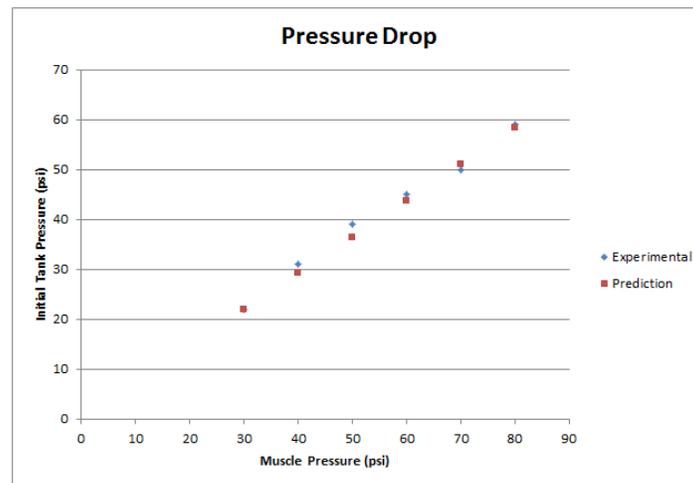

Figure 5: Plot of calculated pressure drops and actual pressure drops for the tanks shown in Fig. 7

Keeping in mind large outlet, tank selection was driven by budget concerns; on hand tank systems were tried to reduce cost. Keeping in mind the goal of an untethered robot, two steel tanks were tried as pressure vessel solutions. However, these tanks were too far too heavy. The final pressure vessel solution was therefore chosen to be two on hand 10 gallon, 200 psi tanks, tethered to the robot.

Figure 6: First iteration of tank design constructed as a proof of concept for high air flow concept.

Figure 7: Second iteration of tank design created a safer testing environment with accurate pressure readouts.

Figure 8: Final iteration of tank design. Safe and allows for multiple jumps without refill.

Two components were machined to facilitate air supply. They are shown below. The first set of components made were manifolds to distribute the air from the tanks to the 14 muscles. The second set of components made were mechanisms to open the tanks. Pneumatic pistons actuated by solenoids open ball values at the tank outlets. Components were machined to mount the piston, and to connect the piston to the valve.
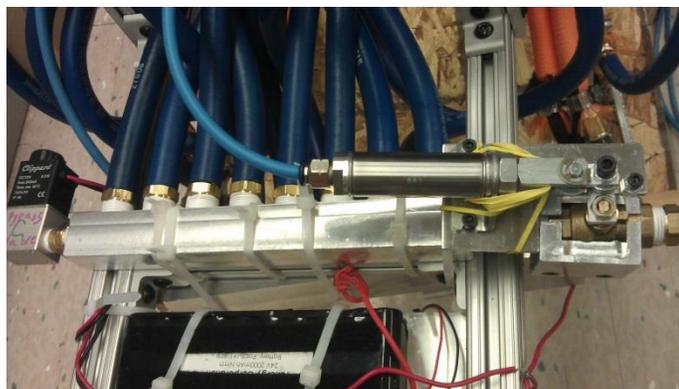

Figure 9: Manifold and pneumatic actuator to control airflow from air tanks to muscles.

An effort was made to use flexible tubing to feed air from the tanks to the muscles. Early prototyping revealed that stiff tubing causes adverse forces and restricts the movement of the links. However, it is challenging to find very flexible tubing that is rated at 60 psi.

Chassis and Leg Design

The chassis and legs of the jumping tiger robot were designed with some key ideas in mind; the design needed to be adjustable, inexpensive, easily manufactured, lightweight, and strong. Understanding that certain dynamic calculations were beyond our calculations and timeframe, we decided on creating more of a prototype style chassis and legs to do our testing with. Design points were dictated by project constraints such as time, capitol, and tools. In *Figure 10* you will see pictures of the main design aspects of the chassis and leg design and a brief explanation of their merit.
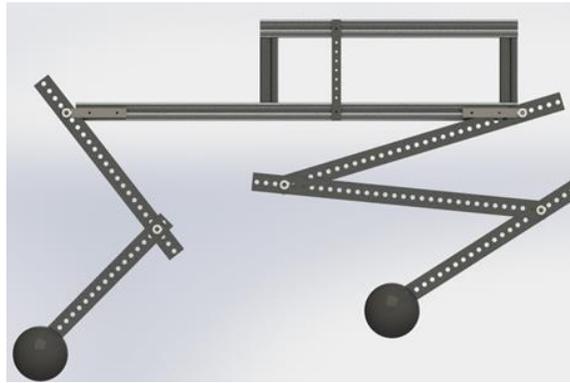
Figure 10: Jumping Tiger Robot 3D model of the body frame and legs.

The chassis is constructed with 80/20 aluminum extrusion t-frame. These parts were chosen because of their ease of assembly, versatility, and adjustability. Circumstances surrounding our muscle development dictated that all of our designs be ready to accept different size muscles. With the available fasteners for the 80/20 frame this material is endlessly adjustable. These accessories and t-frame also make adding our own creations to the frame relatively simple. Along with these features, the 80/20 frame is very sturdy.
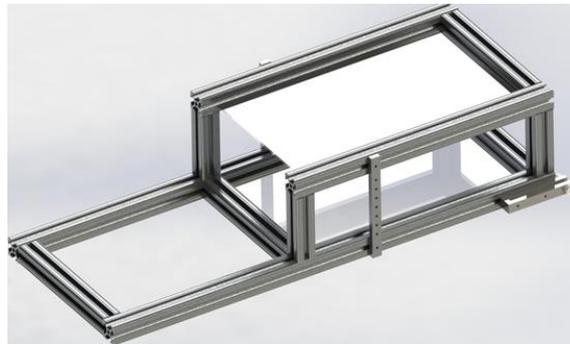

Figure 11: Body frame with acrylic inserts for mounting electronics.

Figure 11 shows the frame holding a piece of acrylic in which we would fasten our electronics too. After constructing this frame we determined that the weight was too great and it was modified to be only a single level. The weight of the 80/20 is the only drawback. This drawback had to be incurred in order to meet other requirements such as cost, versatility, and adjustability.

The legs were designed to be machined out of thin aluminum rectangular plates. Due to the muscle development being done at the same time as design, these were also required to be highly adjustable. Quarter inch holes running the length of the legs was how we resolved to make our legs adjustable. These holes are shown in the *Figure 12* below.

Figure 12: Shows legs design. Mainly illustrates concept of holes running along the length of the leg.

These holes are used for pivot or leg joints, muscle anchor points, and a place to put hard stops. The pivot points are made up of dowel pins, plastic washers, and collar clamps. The plastic washers are placed between the surfaces of the legs that would touch in order to provide a lower frictional effect. The muscle anchor points are made up by using Kevlar rope to tie the muscles to the holes in the legs. Hard stops are made up of nuts and bolts that are placed through certain holes. Having so many points along the legs allows for the ability to test and idealize multiple configurations. The holes in the legs also contributed to their light weight.

The back legs were assembled in a lever actuated manor as shown in *Figure 13* below. Their return was intended to be automatic and made possible by attaching springs in opposition to the muscle levers. The spring return system has not been setup yet due to setbacks in the schedule, but could be implemented in future designs.
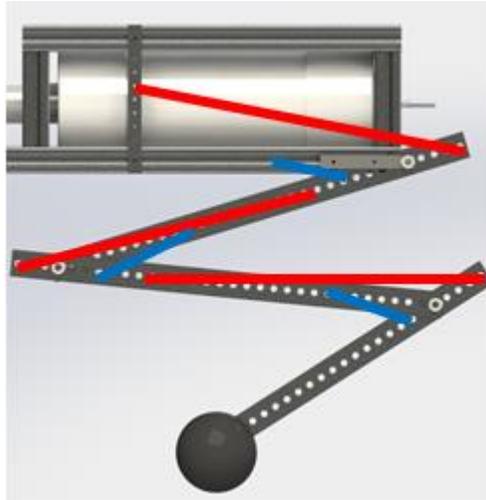
Figure 13: Hind leg with visualized muscle and spring attachment concepts. Red represents red muscles. Blue represents springs.

RESULTS AND DISCUSSION

Our final prototype performed well given the high weight and lack of elastic tendons. While it did not achieve the originally specified ideal jumping length of 1.5x the body length of the robot; it did perform the marginal requirement of jumping 1x body length with proper jump stand angle and muscle timing. The maximum jump distance recorded was 34in. This distance was 6in longer than body length. The robot achieved a jump utilizing only pneumatic air muscles. Through the testing and knowledge we gained of McKibben air muscles we found that with the increased orifice size and muscle timing that this prototype performed well given its weight. We also removed the onboard tanks as the steel tanks we had on hand were too heavy to achieve jumping. A larger budget to afford aluminum tanks would allow this robot to be self-contained.

Spec	Source	Metric	Unit of Measure	Marginal Value	Ideal Value	Preferred Direction
S1	CN1	Horizontal Jump Distance	Feet	1*body length	1.5*body length	Up
S2	CN1,2	Uses Air Muscles	Binary		Yes	
S3	CN3	Sliding Distance After Landing	Inches	3	2	Down
S4	CN4,5	Self-Contained	Binary		Yes	
S5	CN3,6	Overall Weight	Lbs	50	25	Down
S6	CN3,5,6	Overall Length	Feet	4	2	Down
S7	CN3,5,6	Overall Height	Feet	2	1	Down
S8	CN3,5,6	Overall Width	Feet	1		Down
S9	CN8	Resemble a Tiger	Percent	80	100	Up
S10	CN2	Regulated Air Pressure	psi	<60		Down
S12	CN9	Total Response Time to Jump Command	s	0.3	0.15	Down
S13	CN2,9	Solenoid Response Time	ms	50	25	Down
S14	CN2,9	Muscle Fill Time	s	0.1	0.75	Down
S15	CN2,7	Battery Life	# of Jumps	50	100	Up
S16	CN2,8	Four Actuated Legs	Binary		Yes	
S17	CN4,5	Tank can be removed in 5 min, without tools	Binary		Yes	
S18	CN1,2,3,4	Allowable error in leg measurement/adjustment	Degrees	3	1	Down

Figure 14: Engineering specs. Colors represent the completeness of each spec. Green - ideal, yellow - marginal, orange - marginally out of spec, red - out of desired range.

CONCLUSIONS

While this project was successful and the Tiger did jump some improvements are strongly encouraged. It would be nice to see in the future a budget that could support lightening of the frame and onboard air supply tanks. This would achieve a longer jump distance with the current dimensions and control structure. It should be noted that the tiger achieved its best jump when it has its hind legs on the ramp. The ramp is mostly for traction and setting it up the robot at the proper jump angle. Finding the best jump angle combined with muscle delay optimization were found through testing. This project has formed a solid foundation for another group to improve upon in the future with a larger budget.

FUTURE WORK

Future work for this project could go in a few directions. The primary objectives to reach for in any future work would be to optimize muscle exhausting and leg return, reduce weight of entire robot, test elastic muscle connections, remove need for ramp and untether the robot.

One step taken in the future would include optimizing muscle exhaust and spring return of the muscles. With these things optimized, while the tiger is in air it could retract its extended legs into a squatting/sitting position in order to land. This would allow the robot to meet one of the previously unmet needs of landing safely and being prepared to jump again without human interaction.

Another major move in future improvements would be to make the frame and legs out of a lighter weight material or make the frame less heavy in general. This weight reduction would cause an increase in jump distance and height. It may also improve landing. Options for weight reduction that could be attempted would be a conversion to all carbon fiber parts, reduction in aluminum used, or possibly using wood for a body frame.

Testing the advantages of elastic muscle connections would be constructive future work. Finding the correct elastic material for muscle connections could more readily mimic biological muscles. This would add to the accuracy of our bio-mimicking robot. It also has the potential to increase fluidity and power of our jumps. Initial tests would ideally be done with a material with the same spring force of a cat tendon.

An improvement that could be very simple is getting the robot to jump forward without using a ramp. Suggestions for accomplishing this objective include adding friction pads to the hind "feet" of the tiger robot and adjusting hard stops in both the hind and front legs of the robot. Adding friction pads would prevent the robots "feet" from kicking out backwards as seen in testing videos, and instead use that motion to propel the robot forward. Changing the location of hard stops for the legs could aid in aiming the robot at the correct angle for forward and upward motion once the hind legs have better traction with the ground. This combination of testing would be crucial in improving the robots jump.

Lastly, after all other methods of jump improvement have been researched and implemented efforts should be made to untether the robot from the air supply. This would only be able to be accomplished through improving jump quality with the other means discussed previously. Air tanks and regulators suitable for our airflow network would need to be researched. Most likely this investigation would lead to highly expensive options. A brief look into aluminum tanks of air was made and could present a real option.

REFERENCES

Lefeber, D., Karman F.,. "Conception and Realization of Pleated Pneumatic Artificial Muscles and their Use as Compliant Actuation Elements." (1999): n. page. Web. <http://lucy.vub.ac.be/publications/Daerden_PhD.pdf>.

*Lefeber, D., Karman F.,. "Pneumatic Artificial Muscles: actuators for
robotics and automation"*

*Niiyama R., Nagakubo A., Kuniyoshi Y., "Mowgli: A Bipedal Jumping and Landing Robot
with an Artificial Musculoskeletal System." (2007): 2007 IEEE International Conference on
Robotics and Automation*

Engineers Edge http://www.engineersedge.com/fluid_flow/volumeetric_flow_rate.htm 2013

Pritchard P., Leylegian J., "Fox and McDonald's Introduction to Fluid Mechanics" 2011, Chapter 6

ACKNOWLEDGMENTS