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Actuator Trade-Off Analysis for DARPA/BOSS Prototype II

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14. ABSTRACT

The servomotor actuation method used in the first flight prototype zoom lens was chosen because it is simple, small, lightweight, easily available, and can be rapidly integrated into existing UAV systems. Unfortunately, it has proven to be unsatisfactory in several ways. Commanding the servo to positions outside of its displacement-force envelope results in the PID controller "hunting" for the commanded position and burning out the motor. The gearing system linking the servo and plunger is rudimentary and does not allow for much precision in positioning, despite the digital control used in recent versions of the prototype. The form factor of the servo requires it to be placed outside of the optical assembly and complicates the mechanical interface of actuation components. Finally, because model aircraft hobbyists are the main market for these servos, rather than the research or manufacturing communities, very little technical information on the construction or operation of them can be obtained from the manufacturer. An actuator trade-off analysis was undertaken to identify actuation technologies that may better suit our objectives in the next prototype (Prototype II)

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DARPA/BOSS Project Phase II
Actuator Trade-Off Analysis for Prototype II
Revision 1.2 – 13 February 2006

1. Summary

The servomotor actuation method used in the first flight prototype (Prototype I) was chosen because it is simple, small, lightweight, easily available, and can be rapidly integrated into existing UAV systems. Unfortunately, it has proven to be unsatisfactory in several ways. Commanding the servo to positions outside of its displacement-force envelop results in the PID controller "hunting" for the commanded position and burning out the motor. The gearing system linking the servo and plunger is rudimentary and does not allow for much precision in positioning, despite the digital control used in recent versions of Prototype I. The form factor of the servo requires it to be placed outside of the optical assembly and complicates the mechanical interface of actuation components. Finally, because model aircraft hobbyists are the main market for these servos, rather than the research or manufacturing communities, very little technical information on the construction or operation of them can be obtained from the manufacturer. This lack of information made it difficult to produce designs with performance characteristics that could be predicted before fabrication and testing.

An actuation Trade-off Analysis (TOA) was undertaken to identify actuation technologies that may better suit our objectives in the next prototype (Prototype II). The main properties considered were maximum displacement, maximum blocked force, mass, volume, power consumption, and complexity of control. Other considerations were availability of the actuator, availability of information about the actuator, cost, and simplicity/complexity of the device.

The Design Requirements (DRs) for this study were:

- Minimum Blocked Force: $F_{Bmin} = 20N$
- Minimum Displacement: $D_{min} = \pm 0.75mm$
- Maximum Length Along Optical Axis: $L_{max} = 10mm$
- Maximum Mass: $m_{max} = 22g$ (mass of the current system, including gear train)

2. Plot of maximum displacement (D_{max}) vs. maximum blocked force (F_{Bmax})

The properties of a wide variety of actuators were recorded and grouped according to technology type. The technologies examined included both advanced (materials based) and more traditional (electromagnetic) that are currently available on the market. Specific devices were chosen that were representative of each technology type, with preference given to those closest to meeting the design requirements for our application.

The key DRs that constrain our actuator choice are the blocked force and displacement. A plot was generated (FIG. 1) to show the relative properties of all actuators (not including servo and stepper motors) in the study. The region on the plot satisfying the actuation DRs has been highlighted.

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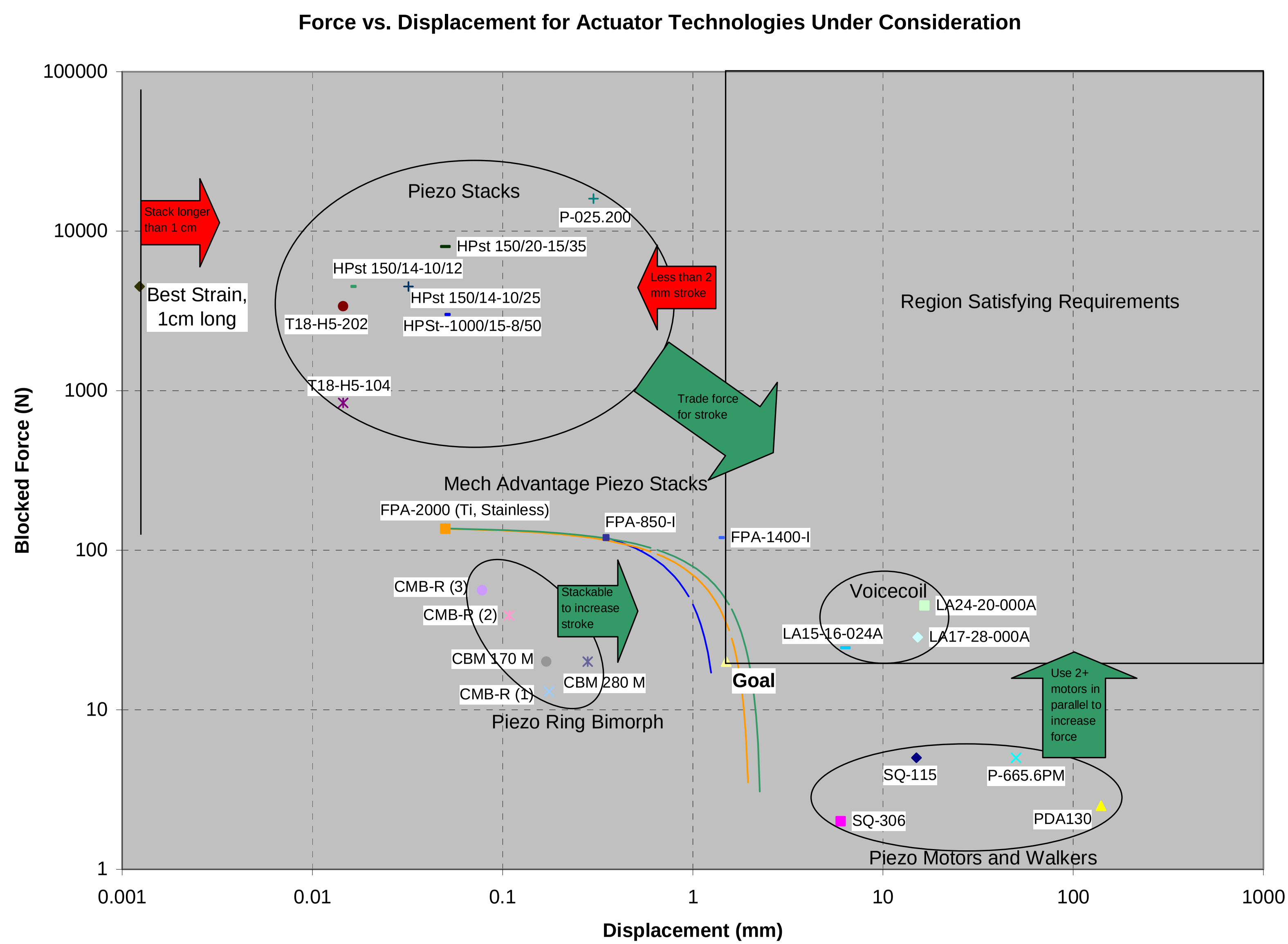
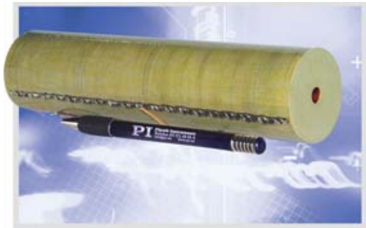

Force vs. Displacement for Actuator Technologies Under Consideration
Blocked Force (N)
Displacement (mm)
100000
10000
1000
100
10
1
0.001
0.01
0.1
1
10
100
1000
Stack longer than 1 cm
Best Strain, 1cm long
Piezo Stacks
P-025.200
HPst 150/20-15/35
HPst 150/14-10/12
HPst 150/14-10/25
T18-H5-202
HPSt--1000/15-8/50
T18-H5-104
Less than 2 mm stroke
Trade force for stroke
Region Satisfying Requirements
Mech Advantage Piezo Stacks
FPA-2000 (Ti, Stainless)
FPA-850-I
FPA-1400-I
CMB-R (3)
CMB-R (2)
Stackable to increase stroke
CBM 170 M
CBM 280 M
CMB-R (1)
Piezo Ring Bimorph
Goal
Voicecoil
LA24-20-000A
LA15-16-024A
LA17-28-000A
Use 2+ motors in parallel to increase force
SQ-115
P-665.6PM
SQ-306
PDA130
Piezo Motors and Walkers

3. Actuator Evaluations – Advanced Technologies

Piezoelectric Stack

Advantages:



- No moving parts
- Displacement is directly proportional to the applied voltage allowing simple control
- Large available blocked forces
- Wide temperature range of operation
- Low power consumption
- Almost no power is required to maintain position
- Very reliable
- Commanding a position outside of the force-displacement envelope results in a closest approach solution

Disadvantages:
- Small displacement (strain). The best strain identified in all of the piezoelectric stack actuators examined in this study was 0.124%.
- These actuators tend to be quite heavy, due to the high density of the piezoelectric ceramic.
- The available force decreases linearly with displacement, from max F at D=0 to F=0 at max D.
- Requires a high voltage supply (~200V)
- The control electronics are not compatible with the standard PWM interface found in servo motors, so a new communications pathway to the UAV payload would have to be developed. If RS-232 can be used then this would not be difficult, but a different protocol would be.

Findings:
- All of the identified stack actuators satisfied the force DR for most of their displacement ranges, but the total available displacement fell far short of the DR for all of them.
- The displacement available from a stack actuator with the best observed strain and satisfying the 10mm length limitation would produce a maximum displacement of only 0.0124mm.
- A variety of mechanical advantage approaches were investigated with the aim of trading some of the large force available from the actuators for displacement
    - All of the approaches considered were infeasible, due to the large difference between the available and desired displacements. A factor of more than 120 was common.
    - For example, a 3rd class lever with 66% output arm would require a total length of approximately 205 mm to produce 1.5mm displacement at 30N from an actuator capable of 0.0124mm at 4000N.

Sources Include:
- PiezoSystems, Physik Instrumente L.P., PiezoMechanik (US EuroTek, Inc.), TRS Ceramics, Nanomotion, Dynamic Structures and Materials, APC International, Kinetic Ceramics Inc, EDO Corp, Noliac, Cedrat Technologies Groupe.

Amplified Piezoelectric Stack

Advantages:
- Few moving parts
- Displacement is directly proportional to the applied voltage allowing simple control
- Much larger displacements than standard stacked piezoelectric actuators
- Wide temperature range of operation

- Low power consumption
- Almost no power is required to maintain position
- Very reliable
- Commanding a position outside of the force-displacement envelope results in a closest approach solution

Disadvantages:

- When the amplification components are included these actuators are quite large and heavy: ~100mm across and ~250g. The high density of piezoelectric ceramic only exacerbates this problem.
- Most of these actuators do not have through holes parallel to the direction of displacement, making incorporating them into the optical assembly difficult.
- The available force decreases linearly with displacement, from max F at D=0 to F=0 at max D.
- Requires a high voltage supply (~200V)
- The control electronics are not compatible with the standard PWM interface found in servo motors, so a new communications pathway to the UAV payload would have to be developed. If RS-232 can be used then this would not be difficult, but a different protocol would be.

Findings:

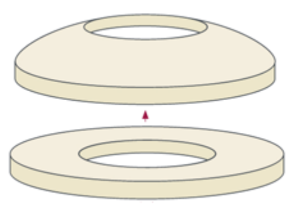
- None of the available amplified piezoelectric stack actuators found would be suitable for our application despite meeting the force and displacement DRs, due to their large mass and volume.
- The commercially available amplified piezoelectric stack actuators support the assertion that long lever arms would be required to generate significant displacements.

Sources Include:

- Dynamic Structures and Materials, Cedrat Technologies Groupe.

<u>Piezoelectric Bimorph Ring Benders</u>

Advantages:



- No moving parts
- Displacement is directly proportional to the applied voltage allowing simple control
- Wide temperature range of operation
- Low power consumption
- Much larger displacements than with piezoelectric stacks
- Almost no power is required to maintain position
- Very reliable
- Commanding a position outside of the force-displacement envelope results in a closest approach solution

Disadvantages:

- Available blocked forces are much smaller (~100x) than with stacks
- The available force decreases linearly with displacement, from max F at D=0 to F=0 at max D.
- Requires a high voltage supply (~200V)
- The control electronics are not compatible with the standard PWM interface found in servo motors, so a new communications pathway to the UAV payload would have to be developed. If RS-232 can be used then this would not be difficult, but a different protocol would be.

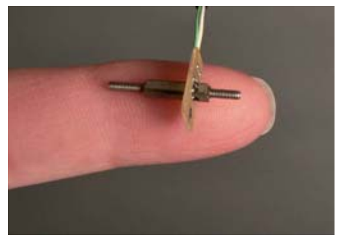
Findings:

- At first glance, this technology falls far short in displacement while barely satisfying the force DR, but:
    - The disks can be stacked to act in series, magnifying the displacement

    - The disks are thin (~1-2mm) so many can be stacked in 10mm to meet the displacement DR
- A stack of 8 Noliac CMB-R(3) disks would come close to satisfying the force and displacement DRs, but fails the mass limitation:
    - 28 disks, for a stack thickness of 33.6mm, F ≥ 20N, D = 1.47mm
    - This would have a mass of almost 320g, which would be far too large.
- These actuators come close enough to the force and displacement DRs to be considered a viable possibility; however the large mass of the required stack would likely rule it out.

Sources Include:
- PiezoSystems, Physik Instrumente L.P., PiezoMechanik (US EuroTek, Inc.), TRS Ceramics, Nanomotion, Dynamic Structures and Materials, APC International, Kinetic Ceramics Inc, EDO Corp, Noliac, Cedrat Technologies Groupe, others.

<u>Piezoelectric Motors</u>



Advantages:
- Only one moving part, 7 parts in total
- For all practical purposes, infinite displacement
- They require no power to hold position
- Motor is very small (~5mm diameter) and lightweight (~2g)
- Commanding a position outside of the force-displacement envelope results in a closest approach solution or shutdown, not damage
- The available force is constant over the entire displacement range
- The control boards are generally RS-232 compatible, so redesigning the UAV Payload – GCS interface would not be a difficult project.

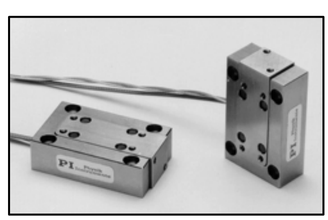
Disadvantages:
- The available maximum force is small: ~5N
- Requires a control board 2"x3" (in the future it will be an ASIC)
- They are expensive, ~ $400/each + electronics.

Findings:
- These motors can be used in parallel, acting on the same component to produce a larger total force. Four SQ-115 motors from New Scale Technologies would provide F = 20N and D = 15mm.
- This may be a viable route, though the total weight and volume of the four motor system would leave little advantage over a traditional servo or stepper motor approach.
- The simplicity of using linear actuators that do not require reduction gearing makes this an attractive possibility.

Sources Include:
- New Scale Technologies, EDO Corp, Kinetic Ceramics, Piezo Systems, Cedrat Technologies Groupe, the Brady Group, Physik Instrumente L.P., others.

<u>Piezoelectric Walkers</u>

Advantages:
- Few moving parts
- For all practical purposes, infinite displacement



- They require no power to hold position
- Motor is small (~10mm x 5mm x 10mm) and moderately lightweight (~10g)
- Commanding a position outside of the force-displacement envelope results in a closest approach solution or shutdown, not damage
- The available force is constant over the entire displacement range
- The control electronics are not compatible with the standard PWM interface found in servo motors, so a new communications pathway to the UAV payload would have to be developed. If RS-232 can be used then this would not be difficult, but a different protocol would be.

Disadvantages:

- The available maximum force is small: ~5N
- The geometry of the device is difficult to incorporate into this design. It requires a strip of specially coated material on which to act.
- They are expensive, ~$500 each.

Findings:

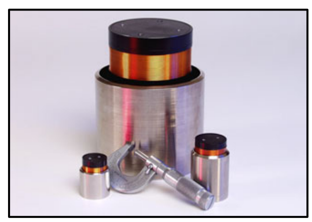
- These motors are better suited to translation stages than our device, in part because of the need for a high precision gap between the motor and moving component.

4. Actuator Evaluations – Traditional

Electromagnetic Voicecoil

Advantages:

- Well understood, mature technology
- Simple to control – force is proportional to current flow through the coil.
- The forces and displacements available from small devices meet the design requirements.



Disadvantages:

- Power consumption is proportional to force, so maintaining the lenses at partial compression would draw considerable power.
- They tend to be heavy, because of the metal components and/or magnets required
- They often produce magnetic fields that can interfere with the operation of other electronics nearby.
- The control electronics are not compatible with the standard PWM interface found in servo motors, so a new communications pathway to the UAV payload would have to be developed. If RS-232 can be used then this would not be difficult, but a different protocol would be.

Findings:

- There are two varieties, moving coil (NCC) and moving magnet (NCM). NCC actuators tend to be wider, shorter, and provide less force with longer strokes. NCM actuators tend to be longer, narrower, and provide more force with shorter strokes.
- These are the only actuators identified that, as a single device, fall inside of the design requirements region of the force-displacement plot.
- The geometry (no through hole) and high weight and power consumption may make them difficult to use in our application, but smaller, lighter versions may be found with continued searching.

Sources Include:

- BEI Kimko Magnetics, H2W Technologies, Baldor Electric Company, Western Components Inc

<u>Integrated Stepper/Leadscrew</u>

Advantages:
- Well understood, mature technology
- They are robust, well integrated packages
- Available as relatively small, lightweight units – often as OEM
- Large displacements and moderate blocked forces are available
- No need to convert angular displacement and torque to linear displacement and linear force.
- Good specifications and application information is available from manufacturers.

Disadvantages:
- Very few of these devices are available with integrated closed loop control, so separate control electronics are necessary.
- The geometry of the device may make it difficult to integrate into the optics assembly directly.
- The control electronics are not compatible with the standard PWM interface found in servo motors, so a new communications pathway to the UAV payload would have to be developed. If RS-232 can be used then this would not be difficult, but a different protocol would be.

Findings:
- If the combined weight and volume of both the actuator and the control electronics is comparable to the servo currently in use, then this would be a good option.
- One good example is the Thompson Airpax model 26DBM-K, for which the specifications are:
    - 19.2 N maximum force, 8.3N unenergized holding force
    - 13.2 mm maximum displacement
    - 12 VDC operating voltage, 3.4 W power consumption at maximum force
    - 34 g device weight

Sources Include:
- Thompson Airpax Mechatronics, Danaher Motion, BEI Kimko Magnetics, H2W Technologies, MicroMo, Eastern Air Devices Inc.

5. Motor Evaluations

When using a torque source to drive this system, there are three practical ways to convert that torque into linear force and motion: a rack and pinion, worm and worm gear, and a screw and nut. The last option is preferable because it provides more accurate control, more compact mechanics and simpler reduction of off-axis moments on the plunger assembly. Of greater significance is the advantage friction may provide in the worm gear and screw and nut approaches. The motor duty cycle is expected to be quite small – less than 10%. This means that the larger friction from a screw and nut assembly can be an advantage, because it will reduce power consumption by the motor the other 90% of time when the motor is working to maintain a static position. The increase in power required to move the assembly should not be a problem unless it is extraordinarily high and dictates the use of a much larger (and hence impractical) motor.

The rack and pinion worked in the first prototypes, but there were problems. In order to mate the pinion and rack properly, a large (~5mm dia) pinion was used. This meant that a small angular displacement produced a large linear displacement, making the system very sensitive to changes in the commanded position. The necessary orientation of the servo with respect to the optical assembly made the overall assembly somewhat cumbersome and less stable. Also, the rack and pinion arrangement is more difficult to integrate into a small package where undesired motions are constrained. Finally, the rack and pinion makes it difficult to apply forces through the center of mass of the plunger assembly, so there are torques that cause binding if there is any slack allowed. These issues can be overcome, but the advantages of the screw and nut make it the more desirable option.

In order to evaluate servo and stepper motors, we must develop a modified (angular) version of the design requirements listed in the first section. The first step is to establish the minimum torque that will be required. Let us assume we will be using the screw and nut approach. The force required to turn a screw of radius r, pitch p, friction coefficient μ, load Q and lever arm R is:

$$F = Q\frac{p + 6.2832\mu r - p}{6.2832r + \mu p}\frac{r}{R}$$

This assumes the worst case scenario, i.e. the directions of the load vector Q and screw travel are the same. All units are in mm or N. Next, we insert our DR from the first section and some reasonable (standard metric) values for the rest of the parameters:

- Linear force required, Q = 20N
- Screw nominal radius, r = 1.5mm
- Screw pitch, p = 0.25mm
- Friction coefficient (assume lubricated steel screw on steel helicoil inserted in Delrin), μ = 0.16
- Lever arm for the torque, R = 1.5mm

From this we have a minimum force applied to the shaft of 3.74N or 5.62N·mm if applied directly to the shaft circumference.

Based on the screw pitch, we can also say that the DR for angular displacement is:

$$D_a = 2\pi\frac{\pm D_{\min}}{p} = 2\pi\frac{\pm 0.75mm}{0.25mm} = \pm 6\pi \text{ radians}$$

Thus the design requirements for servomotors and stepper motors in this application, assuming the use of a screw and nut arrangement to produce the linear force and displacement, are:

- Minimum Blocked Torque: T_{Bmin} = 5.6N·mm
- Minimum Displacement: D_a= ± 6π rad
- Maximum Length Along Optical Axis: L_{max} = 10mm
- Maximum Mass: m_{max} = 22g (mass of the current system, including gear train)

<u>Servomotors</u>

Advantages:

- Well understood, mature technology
- Simple to control – they generally respond to pulse-width-modulated (PWM) signals that are easy to generate and require little in the way of electronics. UAVs are already set up to produce compatible PWM control signals and interface them with the ground control station.
- Most have an integrated PID controller for closed loop control
- Are designed to achieve a commanded position, rather than a commanded torque.

Disadvantages:

- Outside of the hobby market, it is difficult to find small, lightweight devices… those for robotics tend to be heavy and those for full scale aircraft tend to be large.
- The limited angular displacement (less than ±90°) makes mechanical coupling of the servo to a plunger assembly difficult to do in a way that is both robust and simple. For example, the screw and nut assembly is not an option because achieving the required linear displacement would require far too large a screw pitch to be practical.

- The servo will consume power whenever force is required to maintain the output shaft position, and the current drawn is proportional to the required force.

Findings:
- While a hobby aircraft servo worked well for early prototypes, we should move to a more robust actuation method that provides greater control over position and force.

Sources Include:
- Futaba, Hitec, Airtronics, ServoCity, and many industrial/aerospace servo manufacturers.

<u>Stepper Motors</u>

Advantages:

- There are many small, lightweight stepper motors available on the market.
- Control is more complicated than with a servo, but not significantly so if a control board with RS-232 interface is used.
- Available angular displacement is unlimited, though quantized.
- Position can be controlled accurately, as long as it is an integral multiple of the smallest step for a given motor.
- Stepper motors are used in many commercial and laboratory devices, so manufacturers can provide good information about their operation and guidelines for their use.
- They do not require high voltages, 9 to 24V is typical
- The torque density of modern designs tends to be quite high.

Disadvantages:
- The stepper will consume power whenever force is required to maintain the output shaft position, and the current drawn is proportional to the required force.
- Most stepper motors do not come with a gear reduction, which is often (but not always) necessary to achieve the required torque. In this application a gear reduction may be required and would increase the mass and volume of the system.
- The control electronics are not compatible with the standard PWM interface found in servo motors, so a new communications pathway to the UAV payload would have to be developed. If RS-232 can be used then this would not be difficult, but a different protocol would be.

Findings:
- A stepper motor should work well in this application, and there are some models that may not require a gear reduction to produce the torque specified in the design requirements.
- One good example is the MicroMo Electronics AM2224 two pole stepper motor, with the following specifications:
  - 26 Nmm maximum holding torque
  - Infinite angular displacement
  - 3-24V input voltage
  - 43 g device weight

  The problem with this model is that it will require control electronics and possibly a gear head, which will increase both the mass and size of the actuation subassembly. This will be a problem with almost any stepper motor considered for this application.

Sources Include:
- Thompson Airpax Mechatronics, Danaher Motion, BEI Kimko Magnetics, H2W Technologies, MicroMo Electronics, Eastern Air Devices Inc., Parker Hannifin, many others.

6. Conclusions

The information gathered in the TOA was used to make educated estimates of scores for each technology in each of 11 categories. A weight was assigned to each category based on the experience of designing the prototype I device. This information was assembled in a Trade-Off Matrix (TOM) produce total scores that trade the relative advantages and disadvantages of each actuation technology when applied to this project. The results are displayed in figure 2.

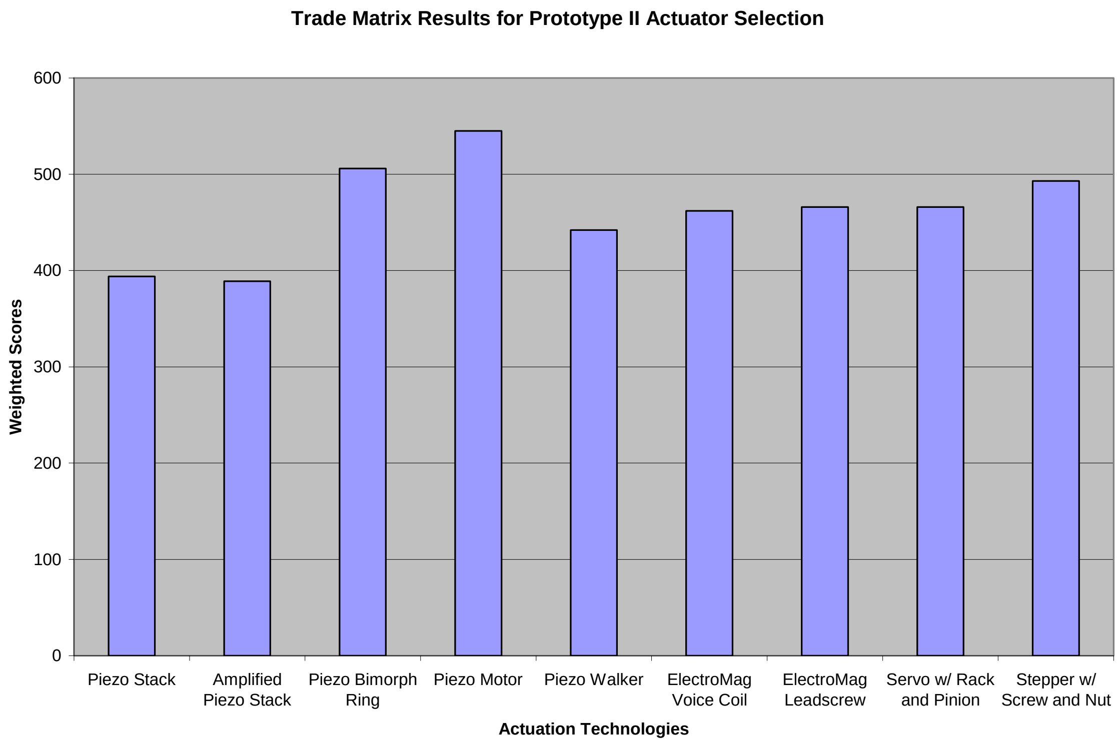


Figure 2

Criteria	Weight Factor	Piezo Stack	Amplified Piezo Stack	Piezo Bimorph Ring	Piezo Motor	Piezo Walker	ElectroMag Voice Coil	ElectroMag Leadscrew	Servo w/ Rack and Pinion	Stepper w/ Screw and Nut
Proximity to Design Requirements	10	0	5	7	8	7	10	10	9	10
Mass	9	2	1	5	9	7	7	6	6	8
Volume	7	3	2	7	9	7	6	6	7	7
Power Consumption in Actuation	5	9	9	9	9	8	5	6	6	6
Power Consumption when Holding Position	7	9	9	9	10	10	1	4	1	4
Complexity of Mechanical Interface	8	10	7	9	7	0	7	6	6	6
Complexity of Control/Power Interface	8	4	4	4	5	5	7	7	10	6
Availability	5	8	7	8	5	8	9	9	9	9
Overload Behavior	5	9	9	9	8	5	6	5	4	7
Novelty of the Technology	3	10	10	10	10	10	1	1	1	1
Cost	5	4	2	3	3	3	7	7	8	7
Total Score for Each Technology		394	389	506	545	442	462	466	466	493

The results of this TOA suggest that the piezoelectric motor, piezoelectric bimorph ring and stepper motor actuation technologies warrant further investigation for the next prototype. The main reasons for their appearance with high scores are the small volumes and masses associated with these technologies, while producing force and displacement combinations that fall in the Design Requirements. It should be noted, however, that the first two technologies (piezo motor and piezo ring) will require multiple devices working in tandem to satisfy the design requirements.

It would also be a good idea to not dispense with the servo motor approach entirely, in case implementing one of the three top technologies turns out to be more difficult or less advantageous than estimated in this study, and because it emerged from the TOM with a reasonable score despite the observed problems.