EXECUTIVE SUMMARY

The Air Force Research Laboratory (AFRL) has begun efforts to develop technologies for bird and insect-sized micro air vehicles (MAVs). One requirement for urban missions is for the MAVs to be able to perch for various mission objectives. The landing environment might be on a branch like object, but could also be a ledge or other horizontal platform. We developed a landing gear prototype to enable landing focused on a 50mm diameter branch as this was perceived as a more significant project goal.

A system was designed and tested based on a compound four-bar linkage which uses a combination of torsion springs for high speed torque, servomotors and a ratchet and pawl, the combination of which articulates a claw-like mechanism which can grasp and secure itself to branch similar geometries.

The device was built with a series of design requirements in mind; repositioning, landing under high stress environmental conditions, take-off assist etc.
INTRODUCTION

The Air Force Research Laboratory (AFRL) has begun efforts in development of technologies for bird and insect-sized micro air vehicles (MAVs). In order to meet its goals for urban missions, the MAVs need to be able to perch for either recharging or for intelligence, surveillance and reconnaissance of stationary targets. The landing environment might be on a branch, but more likely would be on a ledge or other horizontal platform. Either way, the landing will not resemble a roll-out landing, but a perching maneuver much like a bird. Concepts for a landing gear are to be developed for this platform. The landing gear must enable the landing itself, limited ground mobility for repositioning and other maneuverability at the perching site, and possibly incorporate energy harvesting or other functionalities needed for completion of the mission.

Our team from Phoenix Aerospace LLC made the decision to follow a design process which met each design requirement in series based on level of feasibility and attainability, rather than a broad sweeping attempt at one complete unified solution. This decision was made primarily for reasons of efficacy and efficiency because the relationship between design requirements and conceptual development is – pseudo-sequential and this approach seemed most sensible given time constraints. It would have been difficult for us to merge the different concepts into a design that could be prototyped. Since each design requirement is in and of itself rather challenging attempting a global solution seemed risky at best. By meeting the more difficult requirements initially, we would ensure that those get met. The different requirements and their rationales are described in the next section. We felt that the hardest requirement was to perch on a branch and on the ground. Our designs thus focus on meeting that requirement. Crucially, we have not developed the design for a sophisticated takeoff but only to for a landing scenario.
DESIGN REQUIREMENTS

The requirements of this SBIR grant were distilled to 8 major points based on feasibility, tangible and intangible value to the objective, and cost vs. reward. A summary of the major system requirements decided upon is presented below.

1. The landing gear design selected must be able to interface and attach to a quadcopter.
2. The system must be capable of flat surfaces down to a width of 500mm and up to a tilt of 30 degrees. This is based upon an assumption of window ledges and roofing angles.
3. The design must be capable of landing on rigid branches down to 50mm diameter given expected branch diameters.
4. The landing gear must have some mechanism which provides take-off assist for energy efficiency and operational purposes.
5. This device is to be designed for prolonged field use and as such must be capable of multiple take-off and landings without manual reset.
6. Another function of the environmental conditions expected for the MAV and pilot error, the design must be able to withstand a drop from 2m to concrete.
7. For optimal surveillance the quadcopter should be able to reposition on the landing surface/ground.
8. The landing gear must be able to provide stabilizing forces to the quadcopter in winds up to 5kt, such that sustained perching on the landing surface without motors can be achieved.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Drop height</td>
<td>2m to concrete</td>
</tr>
<tr>
<td>Landing surface width</td>
<td>500mm</td>
</tr>
<tr>
<td>Landing surface angle</td>
<td>30 degrees</td>
</tr>
<tr>
<td>Branch diameter</td>
<td>50mm, rigid</td>
</tr>
<tr>
<td>Wind velocity</td>
<td>2.5 m/s</td>
</tr>
<tr>
<td>Force of landing</td>
<td>30 N</td>
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</tbody>
</table>

INITIAL DESIGNS

JAY 1

Azlan and Hiroshi described in their paper\(^1\) a finger mechanism that can pinch and grasp. The distinction is shown in the figure below.

This suggested a basis for a design that could land on curved surfaces by grasping and on flat surfaces by pinching. The paper focused on optimizing the geometry of a finger mechanism so that it can both grasp and pinch effectively. The other interesting aspect of this design is that it is underactuated. Only a single actuator is needed to move a finger. If more fingers are used, the actuators could be coupled, possibly requiring only a single actuator for the mechanism.

From the design presented in the paper, a prototype was developed. The final design is shown below. One of the concerns for the design is the transition from grasping to pinching. The transition occurs if there is any object in contact with the inner surfaces of the finger. This will cause the finger to close around the object, instead of pinching into the surface. The other concern was whether the joints were too free to rotate. Since there are many pin joints in the prototype, there was concern that the mechanism could lock up in an undesirable shape.
A prototype was built and both concerns were validated. Due to imperfections within the fabrication process, the friction within each pin joint was very noticeable. This made it nearly impossible for the transition from pinching to grasping to occur. In addition, the large number of pin joints made the mechanism lock up easily. The mechanism would not transition reliably and the prototype was useful in revealing these problems.

One way to salvage this idea would be to use composite joints where the joint is created by a polymer film sandwiched between two different materials. This technique was revealed to us during a lecture by Professor Aaron Hoover (PhD), and could be explored later. The technique has been used by many teams within academia to create robotic mechanisms and could be adapted for our use. Since we did not have the time necessary to build a competency in making such joints, we did not pursue the idea.
FIGURE 3: PICTURE OF THE JAY 1 PROTOTYPE.

MICHAEL 1

A second prototype was developed by Michael Heyns with different design goals. This prototype was developed separately of Jayesh Gorasia and targeted different requirement areas; branch grasping, horizontal landing and the use of stored energy to provide a take-off assist via spring kinematics.

This design was a small and stable system, low to the ground, with four points of contact for horizontal surfaces and 8 for branches. It used cable driven linkages operated via high-torque servo-motor to actuate the appendages.
The device works via combination of motor-driven linkage actuation, and torsion springs. When the motor turns on the cables in the linkages pull tight, creating a compressive force around whatever object is within the range of the arms. When the motor is turned off the linkages snap out due to the torsional spring force. Mitre gears make up the power transmission and transfer power from the motor to the cable spool.

In the images above the motor has tensioned all the linkages to a folded state. In this state a ratchet and pawl in the power transmission locks the system in the state above. When the motor is back-driven slightly the pawl releases and the 8 torsion springs, 2 on each leg, provide a strong torque to each leg, which then pushes off the ground and ‘launches’ the system into the air.
In the grasping phase the motor applies a tension force to the cable linkages within each arm which causes the linkages to close on one another. There is a small ratcheting mechanism within the geartrain that locks the position of the legs once the motor tension is no longer applied. Small micro-spines on each leg provide additional stabilizing force given surface asperities 5nm or greater. This allows the mechanism to grasp on to any surface. Micro-spines can be fabricated by a rapid prototyping process; shape deposition manufacturing, which permits hard and soft materials to be combined into a single structure.

FINAL DESIGN

OVERVIEW

This design was based on the concept of a hair clip which can quickly snap shut around an object. Many hair clips have curved geometries which pull the hair into its grasps. Further inspiration for this design was found in typical windshield wipers. Windshield wipers have an interesting design where the arm is rigid, but the wiper blade itself is flexible. It makes it possible then for an arm to conform around a shape, making a more stable connection.
FIGURE 4: FINAL DESIGN PERCHED ON A TREE. THIS IS FOR DISPLAY PURPOSES ONLY, AND WAS NOT A SUCCESSFUL TEST.

DESIGN CONSIDERATIONS

A diagram of the first prototype is shown below. The design considerations factored into it’s design are discussed in this section.
The first consideration attacked was producing the short impulse needed to rotate the front femur downward quickly. It was clear that driving a motor would not work, as the desired angular velocity would be too great. Instead, a motor would be used to wind a torsion spring. The torsion spring unwinding will cause the front femur to rotate downward quickly.

To lock the torsion spring in the wound state, a ratchet was used. In order to prevent intersecting parts the motor had to be repositioned; it uses the mechanism shown below.
The gear has an incomplete tooth profile. This prevents the gear from interfering with the pinion when the ratchet is released.

The next consideration is the geometry of the rear leg and front claw. In order to firmly clasp the branch, they need to be curved in a concave shape. When the claw and leg close around the object, the curved surfaces will cause them to be drawn closer together. In the first prototype of this concept, the rear leg and front claw had flat surfaces. This caused an object to be pushed away when the leg and claw came together.
FIGURE 7: CLOSEUP VIEW OF THE CLAWS WHICH ENABLE THE LANDING GEAR TO GRASP ONTO ROUND OBJECTS. THIS DESIGN STILL NEEDS TO BE ITERATED UPON AS IT STILL SLIPS OFF SMOOTH SURFACES.

The final consideration was how to couple the shaft elements. Our options for such small parts were limited. We were using dissimilar metals everywhere, which ruled out welding. There was the option of using silver soldering, but we decided against that as we had no experience within our team. Therefore, we decided to use ¼ shafts for both axles, as this allowed us to use keys to couple rotating elements. This is not ideal, as the shafts are much thicker than we need. Nevertheless, we decided to use the ¼ inch shafts for our prototypes. In future iterations, a splined shaft could be used as that will allow smaller shafts to be used.

GEAR RATIOS, STRENGTH OF MOTOR AND SPRINGS

The driving factor for the strength of the springs and the motor was the speed required for the grasping mechanism. Through consultation with the Vishwa SCOPE team, it was established that the time between when the MAV collided with an object and bounced off was about 5ms.

Using an estimate of moment of inertia of $5 \times 10^{-6}$ kgm$^2$ obtained from Solidworks, the kinematic relationships below was used to determine the necessary

\[
\theta = \frac{1}{2} \alpha t^2
\]

\[
\tau = I\alpha
\]

Assuming that the front femur sweeps through 90 degrees in 5ms to close, that implies that the desired torque on the front femur is 628 Nmm.
Since we wanted to use a hobby servo as a motor, we were limited in our selection of potential motors. The best motor we could find was the Hitec 5085 MG, which had a maximum torque of 421 Nmm. While this was insufficient for our needs, this was the best motor we could find. We decided against using the external gears to increase the torque provided by the motor, as we could not find suitable gears. This would be something to change in the next iteration of the prototype.

The torque requirement for the motor was determined by considering the desired front axle torsion spring strength. The torsion spring’s torque needed to be close to 628 Nmm. Therefore we used a 180 degree CW torsion spring, while had 508 Nmm of torque (McMaster P/N ###). To determine the torque required of the rear torsion spring and the pawl torsion spring, we used a statics analysis as shown below.

Since the moment arms are about the same, the static analysis showed that the torque required from the pawl spring would be the same as the front axle torque spring. This would be unreasonable. Therefore, when the front spring is wound, the pawl will rotate into a hard stop. In this case, the pawl spring is only required to keep the pawl close to the ratchet teeth as it is winding. Any spring could be used for this, and a 45.4 Nmm torque spring was used (McMaster P/N ###).

The rear axle torsion spring was chosen based on the likely force of impact. From the design requirements, the force experienced by the rear leg will be 30N. Therefore, the spring has to be weak enough such that it would move about 10 degrees to disengage the pawl when the leg collides into a branch. Another consideration was misalignment of the rear leg. If the rear leg is misaligned, torque can be transmitted through the pawl from the front torsion spring to the rear torsion spring. This would cause the pawl to disengage, which is not desirable. Using the motion simulation tools within Solidworks, we determined that a 300 Nmm torsion spring would be suitable for our needs (McMaster P/N ###).

ANALYSIS

The main reason for analysis was to meet the mass requirement. The mass requirement drove most of the sizing decisions and material selection.

The most widely used elements in the concept are plates in various shapes. Their two dimensional shapes were driven by function requirements of the design. Therefore, the main parameter that was modified was the thickness of the plates. The first prototype used ¼ inch Acrylic for most of the plates. This was bulky and we were wary of being able to meet the mass requirement.

To iterate on the material choice, we used the beam deflection equation:

$$\delta = \frac{PL^3}{KEI}$$

where K is a constant depending on the exact boundary conditions. Assuming that the beam is rectangular, and that length is proportional to mass, we get the following relationship:

$$\delta = \frac{P \rho^3}{KEI}$$
Therefore, the best material for a stiff and light plate is determined by the cube root of stiffness divided by density, $\sqrt[3]{E/\rho}$.

![Material Selection Chart](image)

**FIGURE 8: YOUKG'S MODULUS VERSUS DENSITY MATERIAL SELECTION CHART.**

Using the material selection tools provided by Ashby, we found that composites and metals were the best choices for us. To make manufacturing easier, we chose to use 6061-T6 aluminum alloy. In addition, we had a lot of experience using it and were comfortable with its manufacturing characteristics.

To verify our material choice, we ran an FEA study on the front femur. The femur was constrained at the front axle end, while the claw end experienced a 30N load. As the following figures show, there is insignificant deflection in the front femur, and most of the part experiences very low stresses. The stress concentrations are entirely near the keyway, which is expected as it has sharp corners.

Based on the analysis of the front femur, we decided that the rest of the plates would not have problems. They should be stiff enough and not experience high stresses.

WHICH MEANS THAT THE THICKNESS OF THE PLATE IS SUITABLE. STRESS CONCENTRATIONS AROUND THE KEYWAY WERE EXPECTED AS THE GEOMETRY WAS SHARP THERE.

FEA analysis was also used to choose the material for the claw and rear leg. The additional requirement for these parts was that the materials have the ability to absorb impact. It would not be desirable if the part did not absorb impact well, as it could make grasping difficult. Our FEA analysis was inconclusive and did not help our decision making process. Therefore, we elected to use Delrin as we had that freely available.

TESTING AND DISCUSSION

In assembly of the device some characteristics of the system which need further work were made abundantly clear. Due to the strong presence of springs within the assembly, fitting the parts together proved far more challenging than anticipated due to the loading pre-assembly. Additionally, the initial design included spring pins as a means to maintain radially and axially fixed parts at set distances from one another, however this design was changed to standard solid dowel pins during assembly for ease of use. Unfortunately, due to the small scale of the parts the tolerances on each part was quite complex and required very precise machining, which unfortunately was not the case and many parts were produced slightly out of specification. This results in a lot of plates on pivots which caught on the shafts and caused wear and friction. One of the larger observations in assembly is the pawl. Unfortunately, despite machining from steel, the teeth on the pawl wore out very easily as hardened brass (gear) is stronger than steel (pawl). Finally, initially it was thought that Servo City, who sent us the motor, made an error, however that error was corrected at the last minute and we were able to observe adequate rotation with the servo in the placement indicated above.

FUTURE STEPS

Future work involving this device will be mainly focused on refining the mechanism, further validating the design and creating another comprehensive iteration. More work on the ratchet and pawl mechanism such that it works and is more durable is required, perhaps spring plungers could be investigated. Consolidation of materials from brass, Delrin, steel and aluminum to only one or two material is also desirable. Once these few issues are resolved we can then focus on further issues.

APPENDIX

1. Bill of materials and main subassemblies
2. Videos
   a. Intro – Displaying the CAD model and its different components
   b. Pawl – Showing how the pawl works
   c. Grasping – A simulation of an attempted grasp. Instead of moving the landing gear, the branch is allowed to move to show how the landing gear might move when it tries to grasp.