47th AIAA Aerospace Sciences Meeting Including The New Horizons Forum and Aerospace Exposition
5 - 8 January 2009, Orlando, Florida

AIAA 2009-40

The Sticky-Pad Plane and other Innovative Concepts for Perching UAVs

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A primary limiting factor in the design and operation of small, Unmanned Air Vehicles (UAVs) is energy. Current models have unsatisfactory range and endurance, and other enhanced capabilities must be omitted from their design because there is not sufficient energy to power them. One proposed solution to this energy problem is to imitate birds by "perching", a definition which was broadly stated as any low-energy-expenditure state in which Intelligence, Surveillance, and Reconnaissance (ISR) could be conducted. Over one-hundred innovative perching UAV concepts were generated and assessed for feasibility and potential mission enhancement. The most promising concepts were further analyzed and prototyped. Among those, the Sticky-Pad Plane was the most successful and was prototyped at the alpha and beta levels. It is able to attach to vertical surfaces from straight and level flight, reposition to conduct ISR, then detach from the wall and re-launch into flight without any additional power requirements. The Sticky-Pad Plane is a robust design that is adaptable to a wide range of aircraft configurations and is capable of perching multiple times in different locations during a given mission. The Sticky-Pad Plane has been successfully demonstrated on three separate aircraft, and it has the potential to increase the duration of ISR missions by an order of magnitude or more.

Nomenclature

L_{max} = maximum line length
l = length of operating envelope
k_l = ratio of workspace to operating envelope length
w = width of operating envelope
k_w = ratio of workspace to operating envelope width
h = height of operating envelope
k_h = ratio of workspace to operating envelope height
F_{max} = maximum force
m = mass
g = acceleration due to gravity
k = stiffness
a = length of perching line
b_{cg} = distance from aircraft c.g. to perching line attachment point

I. Introduction

SMALL UAV's, also known as Micro Air Vehicles (MAVs) have recently shown much promise in support of small combat units. Their small, man-packable size enables individual units to have direct control over their own ISR assets, enabling these units to be more flexible and independent. These small units no longer require coordination with, or access to, more cumbersome ISR data collection systems. The ever increasing demand for these devices and the growing list of desired capabilities from the user has recently made MAVs a fertile field of scientific research.

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One consistent request from the user community is for greater endurance. In fact, it has been dubbed the greatest "target of opportunity" by US Air Force researchers[1]. In addition, numerous innovative capabilities have been proposed for MAVs that would provide tremendous mission enhancement, yet these capabilities have so far been omitted for want of the necessary power to operate them[2,3]. This challenge of increasing energy efficiency of MAVs is being attacked on many fronts by mostly traditional approaches such as incremental improvements in battery capacity and efficiency, drive train efficiency, aerodynamic efficiency and lightweight components[4].

In the Engineering Mechanics Department's MAV research group at the US Air Force Academy, we have intentionally avoided these traditional, incremental approaches. Instead, we deliberately follow non-traditional problem solving methods in the hopes of developing innovative solutions that have the potential to provide order-of-magnitude improvements by revolutionizing the way MAVs are employed. These approaches to innovative problem solving, which will be presented, include customer needs research, several diverse concept generation techniques, concept evaluation and selection, analysis, and prototyping.

One proposed solution to this endurance problem is to take a cue from birds, and attempt to perch. Unlike all current UAVs, birds and insects do not remain airborne indefinitely; they rest in strategic locations, where they can continue surveying their domain for predator and prey, all the while conserving energy for when it is most needed [5]. Furthermore, it has been pointed out that as MAVs become smaller, the relevant scaling laws dictate a reduced capacity for fuel, and thus a reduced range and/or mission duration[6]. Therefore, regardless of the improvements made in the aforementioned traditional research areas, as MAVs inevitably shrink in size there will always be a requirement for increased endurance. Therefore, our team set out to pioneer innovative MAV prototypes with the ability to perch. To avoid design fixation we re-defined the term "perch" to mean *any low energy expenditure state in which effective ISR could be conducted*. The team also chose to focus our efforts on perching in urban areas where potential perches are more plentiful.

II. Innovative Design Methodology

Perhaps even more important than the new concepts themselves is the methodology that is used to develop them. This methodology universally promotes innovation, and thus can be applied to any number of engineering problems to produce extraordinary mission enhancement. Therefore, even if the particular problem addressed in this work is not of interest, this process should be relevant to all engineers. With that in mind, what follows is a brief synopsis of the Transformational Design Methodology employed in this research, for more detail see the cited references[7,8].

The single most unique element of this method is the persistent emphasis on innovation during every step of the process. The mechanics of the process are important, but they will yield only mundane results without an environment and attitude that encourages creativity, so this becomes our primary focus. This includes everything from the words we choose to define the problem to how team members are selected to the clothes we wear during brainstorming sessions. Every detail is choreographed to enhance innovation.

An example of this attitude of innovation is evident in the very first step of the process; that of determining the key requirements, or customer needs, of the system. The team did not stop at the traditional customer needs gathering techniques, but went one step further by brainstorming for new, unusual methods. One of the more promising ideas, which the team implemented, was to role-play as a small combat team in an urban setting. This exercise lent insights that would be difficult to gain in a conference room; specifically the team learned that users in combat will have very little attention they can dedicate to commanding a system, so simplicity and autonomy are critical. This finding was reinforced by USAF, USA, and USMC users that the team interviewed.

Several techniques were used to generate initial concepts for perching MAVs. Research has shown that the greater number of concepts that are developed, the greater the chance that an innovative solution will result from the process[9]. Therefore, the team kept the design space as wide as possible at this early stage of development by broadening the definition of perching, as mentioned above, and ignoring feasibility. Brainstorming techniques included traditional techniques such as Functional Decomposition, 6-3-5/C-Sketch, design by analogy, mind mapping, and TIPS/TRIZ[10].

A novel approach we tested was to investigate renowned innovators to use as exemplars such as da Vinci, Martin Luther King Jr., and ancient Greeks. The team focused not necessarily on the exemplars innovations, but on the thought processes and attitudes that led to them. This exercise led to many interesting concepts, one being the "Trojan MAV" described in section III. Another novel technique, called "far-field analogy" seeks to draw ideas from fields that are seemingly unrelated to MAVs. For example, the team considered, what elements of literature, or painting could be applied to MAVs. Finally, Transformational Design Cards (T-Cards)[8] were very helpful in refining the most promising concepts. These techniques were used repeatedly over several months to develop as many concepts as possible, and to refine existing concepts.

After creating a pool of over 100 concepts, the team revisited the customer requirements research and evaluated the concepts on the basis of their potential to fulfill the customer's needs and be feasibly prototyped. A Pugh selection matrix[7] was used to evaluate the concepts and select those with the most promise, which are described in the next section. Throughout the concept refinement phase, many of the brainstorming techniques described above were applied again to solve acute design challenges.

III. Concept Variants

Through the brainstorming techniques described above, the team created 130 original concepts for low energy expenditure ISR, or perching. Some concepts are more promising than others, and some concepts are simply not feasible in the current technology climate. Those concepts that hold the most promise are presented below. The concepts are grouped into two categories; Rev Tech and COTS. Rev Tech, short for revolutionary technology, encompasses those concepts that depend on a key piece of technology that is not currently available, but is on the horizon. COTS, or commercial-off-the-shelf, concepts are those that the team believes could be implemented immediately with existing technology.

A. Rev Tech Concepts:

Gecko-feet Pad - Platform is a typical level flight aircraft with a pusher prop or twin wing props. Aircraft has a hinged gecko foot pad on the nose. When the MAV flies into the structure the hinged pad rotates 90 degrees to orient the MAV along the surface. It is capable of adhering to any surface at any orientation. The pad would be sized to support the weight of the MAV. This technology is in early development and is not yet available for public or commercial use, but has tremendous promise.

Hydrogen Generation - Plane carries two chemicals that react to create hydrogen. The airplane is configured for straight, level flight and deploys a balloon to perch in midair with a gimbaled camera for ISR. The hydrogen is used to inflate a balloon and the reaction byproducts/waste is released to reduce weight. Hydrogen generation technology exists, but must be miniaturized before it will be useful for MAVs.

Bird Visual Manipulation Control - Numerous attempts have been made to utilize live birds outfitted with sensors to perform ISR collection, but these attempts have so far involved manipulating neural control signals to control the birds' flight. This approach has significant implementation and ethical challenges. Our proposal, visualization manipulation, takes a far different approach. Rather than manipulating brain waves, we propose creating virtual reality goggles to be worn by birds that would display the necessary images to persuade the bird to fly in the desired direction. For example, the bird would be trained to fly towards an image of their natural prey. If the operator needed the bird to turn right, the goggles would create that image on the right side of the goggles, and the bird would fly in that direction—effectively controlling the flight path of the bird. Control images could be structures, predators, food sources, etc.

The advantages of this system are feasibility, cost, and applicability. The technology is within easy reach - virtual reality is proven, but would need to be miniaturized. We predict the cost to develop and build a small pair of goggles to be less than that of avian neurosurgery. Applicability is another advantage in that this system can be implemented with bird species that are native to a certain area, and therefore have the necessary survival skills to thrive in that environment. For example, a system could be designed to fit the Peregrine Falcon species (*F. peregrinus)*, a medium sized raptor that is prevalent throughout the world, and familiar to urban and rural habitats[11]. The system could then be mounted on an individual that is native to the theater of operation. ISR systems have been successfully mounted on *F. peregrinus*, with the video images transmitted to a ground station, suggesting the feasibility of this concept[12].

B. COTS Concepts:

Hugging Wings – The platform is a fixed wing aircraft, but with flexible, bifurcating wings. Their two positions of equilibrium are outstretched for flight, and curled up for perching - similar to a tape measure. When triggered, the wings would curl up to wrap around appropriate items such as poles, clotheslines or power lines. Numerous devices exist which demonstrate this bifurcating action, but a means of easily unrolling the wings is needed. Piezo-electric actuators or shape memory materials are possibilities. In addition the acrobatic maneuvers to attach to perch platforms would need to be developed.

Helicopter with Sticky Ball Cannon – A rotary wing MAV would be equipped with a canon to fire projectiles. To perch, the helicopter flies near a vertical surface and fires the projectile cannon that attaches an adhesive mount on a tether. The rotors are stopped and the helicopter is reeled against the surface via the tether.

Weighted Tail Line - The platform is a typical fixed wing MAV, but it drags a grappling hook counterweight from its tail, as shown in Fig 1. When flown low over power lines, tree branches, or the like the tow line impacts the perching platform above the hanging weight. Upon impact, the counterweight swings up to wrap the line around the platform multiple times—the vehicle is left to perch, hanging by its tail where it would conduct ISR. To re-launch, the tow line would be released.

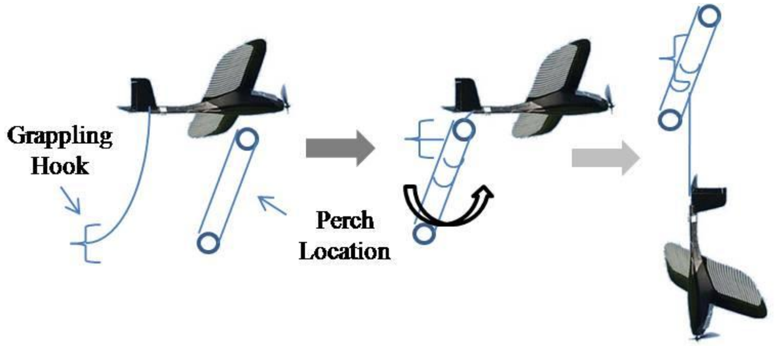

Figure 1. Perching sequence for the Weighted Tail Line Concept. *In the center diagram, the grappling hook is wrapping around a tree branch, securing the MAV.*

Trojan MAV – A typical MAV is equipped with ISR sensors that appear to be damaged. It is designed to crash in a conspicuous area where it is likely to be recovered by the enemy. Once captured and brought back to an enemy hideout, the Trojan MAV will begin transmitting vital intelligence, including video and audio feed, as well as GPS coordinates for a future air strike. GWOT veterans indicate that enemy forces consistently recover damaged US technology and re-use it, so this concept is highly feasible, though any ISR collected would be time sensitive.

SpyderCam - The SpyderCam is a suspended ISR system that uses an internal winching system to control the length of 4 anchor lines, as shown in Fig. 2. The lines can be anchored to any surface. Controlling the lengths of the anchor lines will move the SpyderCam anywhere within the 3D space of the anchors. The SpyderCam will be equipped with its own deployment mechanism to launch the anchors to any surface. The SpyderCam can detach, then re-launch its anchors allowing the MAV to move from one 3D space to another 3D surveillance environment.

Hinged Sticky Pad Aircraft – A COTS MAV without a nose prop (either push prop or twin wing props), and a hinged adhesive pad is attached to the nose. To perch on a vertical surface, the MAV simply flies into the surface. The sticky pad will adhere to the wall, and then rotate via the hinge, allowing the aircraft to hang parallel to the wall, decreasing the moment applied to the sticky pad. The MAV would re-launch by disconnecting from the sticky pad.

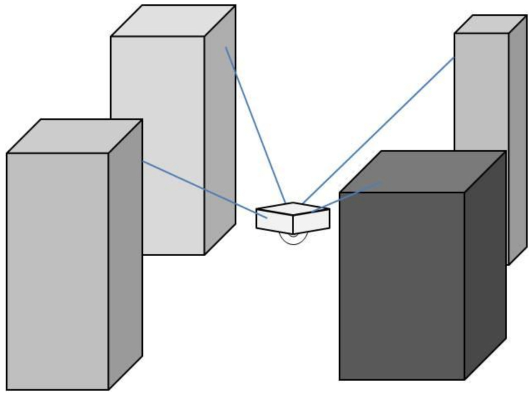

Figure 2. SpyderCam deployed in a city block.

IV. Concept Analysis and Prototyping

Of the promising innovative concepts presented above, the team selected two to prototype. The concepts were evaluated for feasibility and potential mission enhancement, and the Spydercam and Hinged Sticky Pad were considered most promising. Over the course of three months, the team iterated through research, design, manufacturing and testing of these potential perching solutions. The team was successful in demonstrating the feasibility and capability of each concept.

A. SpyderCam

As described above, the SpyderCam is a COTS concept that operates much like existing suspended camera systems: a camera unit is suspended in the air by 4 controlling lines as shown in Fig. X. The length of each line is independently manipulated by external winching systems to control the movement of the unit. The SpyderCam system has greater mission enhancement and has a more practical tactical ISR application over the existing suspended camera systems because it contains independent internal-winching control systems for each control line. This feature gives the SpyderCam the capability to move within the 3D envelope in which it is deployed, and also to move the operating envelope to an adjacent location as shown in Fig. 3. The team tested a number of devices for deploying the anchor lines, including spud guns and crossbows, but did not find a satisfactory mechanism. Future work will need to be done to perfect this re-deployment system, and a bullet fired projectile may be the solution.

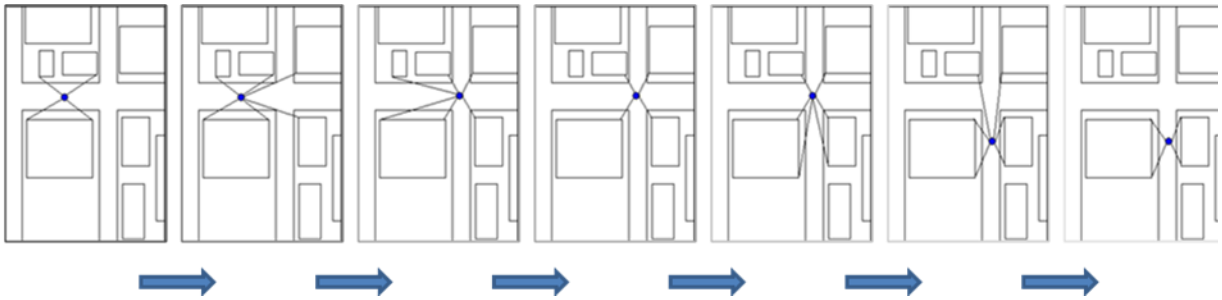

Figure 3. Animation sequence of the SpyderCam traversing through a city block.

To better understand the requirements of the SpyderCam, the team needed to analyze the environment in which the SpyderCam would operate and determine an operating envelope. The team used the application GoogleEarth© to create an average operating envelope based on the largest applicable operating envelope at particular eastern hemisphere, Arabic geographic locations. This average operating envelope is called the minimum operating envelope. The team created a maximum operating envelope by averaging envelopes based on the largest applicable operating envelope at particular western hemisphere locations. Table 1 below shows the various locations utilized in the analysis and Table 2 indicates the operating envelopes for specific deployment options.

Table 1. Potential SpyderCam operating locations and associated envelopes.

Eastern Locations	Operating Location & Dimensions	Max Line Length (ft)	Western Locations	Operating Location & Dimensions	Max Line Length (ft)
Al Ahrar Bridge, Baghdad, Iraq	60'x118 (NE Ramp)	138	Montreal, Canada	200'x60' (Small Block)	198
	135'x100' (SW Ramp)	165		400'x60' (Large Block)	362
	45' (Bridge Width)	93			
Al Azamiyah, Baghdad, Iraq	117'x43' (Intersection)	132	New York, New York	200'x150' (Intersection)	231
	89'x116' (Block)	148		430'x70' (Block)	**389**
	50'x30' (Alley)	91			
Al Jadriya, Baghdad, Iraq	108'x85' (Intersection)	142			
	400'x144' (Block)	**379**			
	86'x50' (Alley)	115			
Baghdad Univ., Iraq	300'x240' (Buildings)	344			
Kadhimiya, Iraq	230'x140' (Open Area)	247			
Karbala, Iraq	60'x122' (Block)	141			
Mosul, Iraq	65'x118' (Block)	140			
Sadr City, Iraq	144'x118' (Intersection)	179			
	50'x18' (Alley)	88			
	124'x120' (Field)	169			

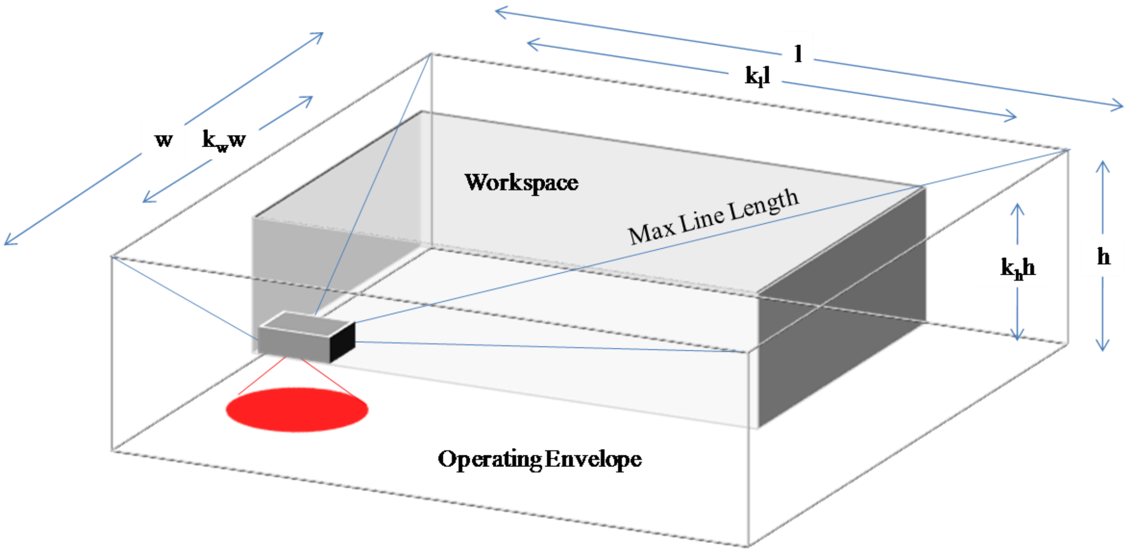

Figure 4. Operating envelope and workspace for the SpyderCam.

This operating envelope analysis allowed the team the ability to determine the amount of line needed on each spool of an operational system, which ultimately affects the size of the SpyderCam, needed spooling mechanism and line strength. Given a potential operating envelope, as shown in figure 4, a workspace can be defined which will have dimensions less than those of the operating envelope, assuming it is not necessary for the vehicle to occupy every location in the envelope in order to survey it. The maximum line length, L_{max} needed to operate in the workspace is:

$$L_{\max} = \left\{ \left[l\left(\frac{1+k_l}{2}\right)\right]^2 + \left[w\left(\frac{1+k_w}{2}\right)\right]^2 + (k_h h)^2 \right\}^{\frac{1}{2}} \tag{1}$$

Where the constants, $k_{l,w,h}$, represent the scaling factor that must be chosen to define the workspace within a given operating envelope. These factors would depend on the field of view and range of the ISR sensors carried by the vehicle. For this analysis, a uniform height, $h = 100ft.$ was used, and $k_l = k_w = k_h = 0.75$. The results of equation 1 for each location are included in Table 1, and proposed values for an operational vehicle are included in Table 2. For the prototype, the team chose a target operating envelope of approximately 10% of the results of this study. This enabled the team to demonstrate the concept indoors.

Table 2. Proposed operating envelopes for the SpyderCam.

Deployability	Operating Envelope	Anchor Line Length
Minimum	300' x 300' x 100'	380'
Maximum	450' x 450' x 100'	560'
Prototype	35' x 35' x 10'	50'

The primary mechanical component of the SpyderCam is the servos, which provide the torque and angular velocity to winch-in the control lines. Other types of actuators were considered for winching, however, the team decided that servos would be best in the SpyderCam prototype because of their integrated gearbox and control system. The next generation of the SpyderCam will likely use brushless DC motors with a custom made control system.

Following the design and analysis presented above, the alpha prototype of the SpyderCam was constructed, as shown in Fig. 5. The frame is constructed from carbon fiber, the servos are standard size R/C servos modified for continuous rotation and the system is controlled with an R/C controller and receiver combination and an operator controlling each servo individually. With anchor lines in place, the prototype is able to lift off from the ground and move in the 3D envelope created by the anchor lines, but it is very difficult to control.

Future research will include developing kinematics for the coordinated motion of all of the actuators in concert to produce the desired motion of the SpyderCam. Such a control algorithm could then be integrated with existing autopilot systems for navigation. As mentioned above, a projectile system is needed for re-deploying anchor lines to new locations. This future work seems well within the capabilities of existing technology.

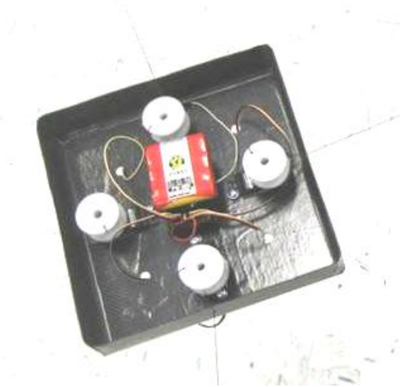

Figure 5. The SpyderCam prototype.

B. The Sticky-Pad Plane

The Sticky-Pad Plane is a system that allows an existing MAV to perch on any vertical surface found in an urban environment and conduct low energy expenditure ISR. When commanded, it can then detach itself from the vertical surface, take off, and either conduct ISR in the flying configuration or relocate and perch again. The Sticky-Pad mechanism does not draw any power from the existing system and does not require any energy for perching whatsoever. Each component is passive and simple, allowing the system to be easily added to any existing MAV *without a tradeoff in capability*.

The Sticky-Pad Plane prototype was implemented on a push prop MAV that is able to fly into almost any vertical surface sustaining a straight on collision at stall speed. Elements to this system include a nose mounted dispenser of sticky pads that attach upon collision, the adhesive on the pad that supports the MAV in the perch, a line that suspends the MAV while collecting ISR, a mechanism that allows the aircraft to detach from the pad and line, and structural elements that enable the MAV to re-gain stable flight. The Sticky-Pad system was successfully prototyped on three different COTS R/C aircraft as listed in Table 3, as an example, the T-Hawk prototype is shown in Fig. 6.

Table 3. COTS R/C Aircraft used as Sticky-Pad prototypes.

Manufacturer	Model	Weight	Wingspan
AeroHobby	T-Hawk	18 oz	40 in
ReadytoFlyFun	SkySeeker GT	13.4 oz	40 in
Megatech	Avion I/O	1.5 oz	16.5 in

Figure 6. Sticky-Pad Plane prototype implemented with an AeroHobby "T-Hawk" R/C plane.

The key to the Sticky-Pad system is the adhesive. The team researched and tested a number of different adhesives, including an assortment of double-sided tapes, glues, bonding adhesives and tacks. However, the best experimental results came from rat glue provided by an extermination materials vendor.

The team investigated the scope of the rat glue's adhesion ability with the hope of determining a material that it would not stick to, but we were unsuccessful. The rat glue is very impressive. This created a challenge for storing the sticky pads on the aircraft, which was solved by creating circular pucks that physically separate the rat glue pads from each other. Figure 7 depicts a cross-sectional view of four pucks stacked together with a gap between each puck to prevent adhesion.

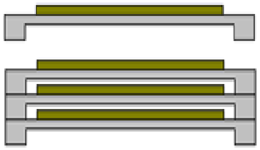

Figure 7. Sticky-Pad pucks stacked together.

Through the course of experimentation, the team discovered that a promising method for decreasing the glue's adhesion is cooling the glue below 38 degrees Fahrenheit. In the future this characteristic could be very useful as a method for detaching the Sticky-Pad Plane, but we considered it infeasible at the present time for our alpha prototype. If a compact method for cooling the pad upon command could be developed, it would be very useful.

Shear testing revealed a vulnerability of the rat glue in that it behaved as a fluid, by continuously deforming until it detached as shown in Fig 8. This creep behavior is nonlinear, as shown in Fig. 9, and a design tradeoff must be considered between perching duration and sticky pad size. A possible solution to prevent creep that requires further research is to support the glue with a mesh structure that would resist shear. Another option is a composite sticky pad combining two adhesives; the rat glue for initial adhesion, and a quick-curing, longer lasting adhesive such as superglue for sustained perching. At the time of this writing, other, superior adhesives were being tested that may eliminate these issues altogether.

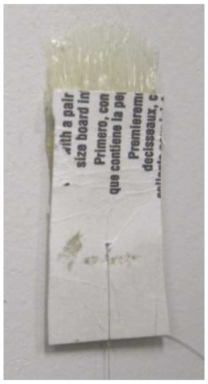

Figure 8. Shear creep in rat glue.

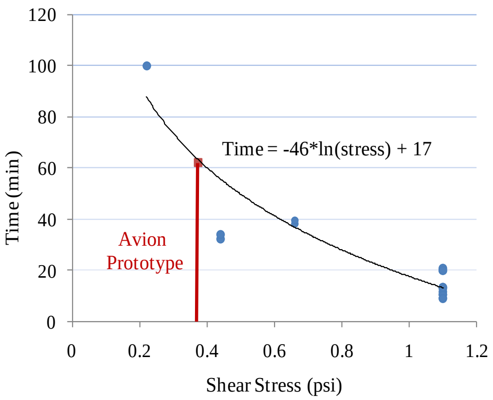

Figure 9. Rat glue shear testing results. *All 18 test specimens were 1in^2 and were adhered to the same finished wood surface.*

To enable multiple perching cycles, several systems were considered that would hold and deploy multiple sticky pads. The requirements for this system included small size, light weight, durability, simplicity, and capacity for numerous Sticky-Pads. Designs that were considered include a conveyor belt system that would rotate pads into place, a linkage that would release a pad each time the aircraft impacted a wall, a rack and pinion feed system, and a ball-screw feed powered by a servo. After testing various mockups, the team settled on a simple mechanism inspired by ball point pens.

The Sticky-Pads are mounted on plastic cylindrical pucks that ride inside a cylindrical casing. The pucks are forced to the front of the aircraft by a spring and have small pegs that ride in a groove to guide them. Upon collision, the outermost puck sticks to the vertical perching surface. The mechanism is further described in Fig. 10. Though somewhat complex, this design has been effective and reliable.

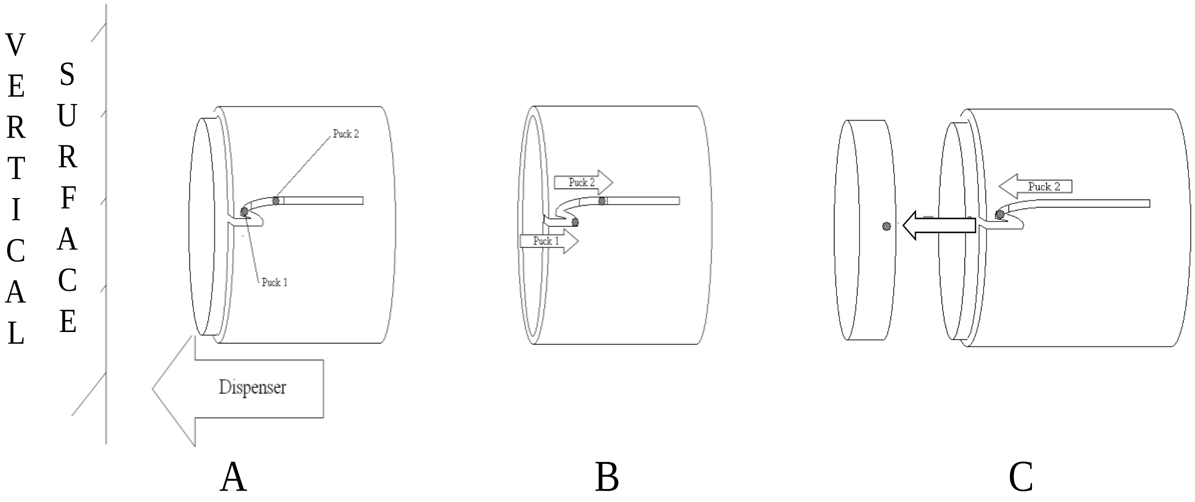

Figure 10. Sticky-Pad puck dispenser system. *The force of the impact with the perching surface(A) acts against the spring, pushing Puck 1 back into the dispenser(B), at which point the guide groove rotates the puck, moving it into a parallel groove that gives it a path to leave the dispenser (C). Puck 2 then takes Puck 1's place at the head of the cue and the plane is ready to perch again.*

During the perch the plane is oriented with its belly against the wall and the nose pointing towards the ground. This orientation is suitable for ISR and facilitates re-launch. To achieve this orientation, the Sticky-Pad (which is nose-mounted) is connected to the tail of the plane with a flexible "perching line". After impact, the puck sticks to the wall and the aircraft falls into the perching position. For the "T-Hawk" prototype, approximately 90% of the

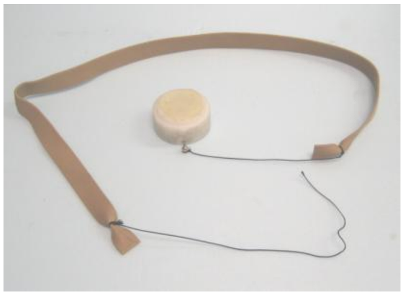

Figure 11. Perching line with rubberband and Sticky-Pad puck.

Figure 12. Razor blade fixed to the elevator to sever the perching line.

line's length is rubber band to add enough compliance to absorb the energy of the fall without breaking the line or tearing the sticky pad off the wall. Given the stiffness of the line, *k*, the length of the line, *a* (typically not more than the length of the aircraft) and the distance from the line attachment point to the aircraft's center of mass, b_{cg}, (assuming the line is attached aft of the center of mass), the peak force applied to the pad and perch line during the fall is:

$$F_{\max} = mg + \sqrt{m^2 g^2 + 2kmg(a + b_{cg})} \tag{2}$$

For the "T-Hawk" prototype, $F_{\max}$ is approximately 7.2 lbs. Conversely, if the maximum allowable force is known, based on the shear strength of the sticky pad, line tensile strength, and/or impact limits of the payload, the minimum required compliance ($^1/_k$) may be calculated. The perching line used on the "T-Hawk" prototype is shown in Fig. 11. The "Avion" prototype did not require additional compliance in the perching line.

During flight the perching line is stowed in a four inch plastic tube which prevents the perching line from catching in the propeller and guides the plane into the correct perching orientation. The tube has a slit down the side that releases the perching line during the fall, and multiple perching lines can be held in the plastic tube. Of course, a compliant perching line is not the only option for controlling the plane's descent into the perching position. Other designs considered include a torsion spring on a reel that unwinds, or housing the perching line in a tight groove that would "peel" away as the aircraft fell.

To re-launch the Sticky-Pad Plane so that it can re-locate or continue mobile ISR, it must be able to disconnect from the wall. As discussed above, if the rat glue could be cooled below 38 degrees Fahrenheit, the glue will detach, but the team did not attempt to implement such a device. Instead, the simplest solution is simply to sever the perching line with a razor blade fixed to the plane's elevator, as shown in Fig. 12. When desired, the operator (or autopilot) simply commands the elevator down a few times and the plane begins to fall.

At the moment the perching line is cut, the aircraft is pointed nose down, towards the ground. The aerodynamics of the particular aircraft involved will determine the minimum vertical height needed to successfully achieve straight and level flight. As one would expect, the largest prototype required the most height, approximately two stories, or 25 feet, and the small "Avion" prototype needed only 8 feet. Although these heights depend mostly on the airframe, certain modifications can be done to improve the takeoff height. Increasing the elevator surface and throw, adding wing flaps or a high lift airfoil, and increasing the angle of attack in the perch position are all options that were tested. The last modification involved attaching large landing gear to the "T-Hawk" prototype. The landing gear held the aircraft out away from the wall approximately 8 inches, effectively increasing the angle of attack as shown in Fig. 13.

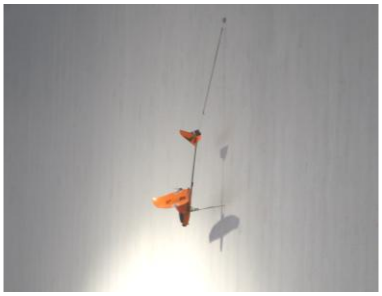

Figure 13. "T-Hawk" prototype perching from a sticky pad.

Figure 14. The successful "Avion" prototype.

As previously mentioned, the integrated Sticky-Pad Plane was implemented on three separate aircraft. The "Avion" prototype was the most successful, and demonstrated the complete functionality of all elements of the perching system by perching, re-orienting and re-launching. It has done so consistently and reliably. The other two prototypes, the "T-

Hawk" and "SkySeeker" were able to perch on a vertical surface, re-orient for ISR, and detach from the wall, but struggled with the re-launch phase. The "T-Hawk" prototype demonstrated the ability to re-launch from the perch position during numerous subsystem tests, but it never successfully re-launched during integrated testing. We are confident that further refinement and better equipment would be more successful. Nevertheless, the "Avion" prototype, shown in Fig. 14, was very successful and definitively proves the feasibility of the Sticky-Pad Plane.

V. Conclusion

We aimed our sights at the largest "target of opportunity" in small UAV research; vehicle endurance. After determining customer needs, the stated team mission was to pioneer an innovative prototype for sustained low-energy tactical ISR in an urban environment. The team applied an innovative design methodology which directly resulted in numerous novel concepts. For example, although some insects are known to deliberately crash land, it is not a heavily utilized technique in aeronautical design, if anything, it is vigorously avoided[13]. However, our team's philosophy was to include such ideas even if they initially appeared to be the opposite of a solution. This novel approach led to a highly successful prototype, the Sticky-Pad Plane, with potential for vast mission enhancement. Three concepts, Bird Visual Manipulation Control, the SpyderCam and the Sticky-Pad Plane stood out for their feasibility and potential mission enhancement. Bird Visual Manipulation Control was not prototyped because it is beyond the scope of the authors' expertise, but we are enthusiastic about the concept and hope it will be further developed by someone with the means to do so. The SpyderCam and Sticky-Pad Plane were prototyped successfully. The SpyderCam provides extended-duration ISR by employing a suspended platform capable of translating in 3D space. The Sticky-Pad Plane uses a dispenser mechanism that allows a small RC aircraft to impact a vertical wall nose-first and hang nose-down from a dispensable adhesive puck.

Prototyping of the SpyderCam and Sticky-Pad Plane revealed the operational strengths and weaknesses of both concepts. The SpyderCam provides a highly maneuverable ISR platform that is unaffected by environmental factors such as wind and is far more energy efficient than airborne vehicles. The ability to redeploy the anchor lines is an unproven concept that requires further exploration, and a comprehensive autopilot control system must be developed, but the SpyderCam will provide a unique capability for small combat units engaged in urban combat. The Sticky-Pad Plane concept has successfully been proven. The next spiral of development should include improving the adhesive to mitigate the creep problems, then integrating the concept on an autonomous UAV with ISR capability. The endurance gains could then be demonstrated which we predict will be at least an order of magnitude improvement. If these two concepts are pursued, we believe they could be enhancing missions for our troops within the next five years.

Acknowledgments

The authors would like to thank Dr. Robert Sierakowski and Dr. Greg Abate of the Air Force Research Laboratory, Munitions Directorate at Eglin Air Force Base, Florida for their guidance and support of this research.

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