Design Optimisation of a Reconfigurable Perching Element for Vertical Take-Off and Landing Unmanned Aerial Vehicles

Mehmet Ali Erbil, Stephen D. Prior and Andrew J. Keane

Reprinted from

International Journal of
Micro Air Vehicles

Volume 5 · Number 3 · September 2013

Multi-Science Publishing
ISSN 1756-8293

Design Optimisation of a Reconfigurable Perching Element for Vertical Take-Off and Landing Unmanned Aerial Vehicles

Mehmet Ali Erbil, Stephen D. Prior and Andrew J. Keane
Aeronautics, Astronautics and Computational Engineering, Faculty of Engineering and the Environment, University of Southampton, Southampton, SO17 1BJ, United Kingdom

ABSTRACT

Vertical Take-off and Landing (VTOL) multi-rotor rotary-wing vehicles face many challenges such as harsh weather conditions and low endurance which affect their overall performance and usability. The current usage of these types of small Unmanned Aerial Vehicles (sUAVs) has changed to an urban and cluttered environment, which the larger fixed-wing UAVs cannot access and gain the required data. With interesting flight regimes such as perching, small man-portable UAVs have found their way into the military and the ever growing civilian sector. This paper aims to provide a method of setting design parameters for a reconfigurable perching element, which replaces the current landing gear on a VTOL UAV which has a maximum take-off mass (MTOM) of <1.5 kg. These design parameters are used to create concepts along with various different grasping methods to cover the design solution space. A weighted matrix method was applied for the design selection and optimisation process, where carefully selected criteria and weightings were chosen to give the VTOL UAV the ability to perch on top of lighting columns, which are a common form of street furniture found in most urban environments.

1. INTRODUCTION

Perching is a highly complex manoeuvre which birds execute on a daily basis and can be split into two different stages: flight control planning and grasping. The flight control planning aspect is the recognition of the perch site and executing the manoeuvres required to attain the perch. The grasping aspect is the physical connection between the Unmanned Aerial Vehicle (UAV) and the perch site. A perching manoeuvre is a highly desirable capability as it can lead to a perch-and-stare system which can conduct extended reconnaissance missions. Furthermore, a perching UAV can also harvest energy either with the use of photovoltaics (PV) or inductive charging [1, 2].

Small man-portable UAVs which are used to survey local areas for extended reconnaissance missions are required to hover in a location for long durations of up to three hours as required in the UAVforge 2012 competition [3]. Hovering is a capability which small fixed wing UAVs do not have, but vertical take-off and landing (VTOL) UAVs do. Hovering for extended periods seriously affects the endurance of the UAV. Langkamp and Cetinsoy et al highlights that cruising at 6.9 m/s compared with hovering, uses 1/6th less power consumption on a 1 kg Aeroquad multi-rotor UAV [4, 5]. By allowing the system to perch, a UAV could save 95% of its power consumption when performing the same surveillance task (figures based on a UAV drawing 18 A at hover and 1 A in a perched state, transmitting only video) [6]. The key to this operation is to execute a perching manoeuvre automatically when required. The Defense Advanced Research Projects Agency (DARPA) and Naval Warfare Systems Center Atlantic (SSC Atlantic) collaborated together to create a crowd sourcing competition called UAVForge 2012 which encouraged companies, hobbyists, students and all other members of the public to take part in developing an Unmanned Aerial System (UAS) which can perform a long distance perch and stare mission. Page says that the thought process behind this competition began back in 2008 when they awarded AeroVironment $4.6m to develop a UAV capable of “hover/perch and stare” [7].

Along with UAVForge 2012, other competition based challenges have arisen in order to tackle the difficult task of perch and stare. The UK Ministry of Defence's - Defence Science & Technology Laboratory (DSTL) released in September 2011 details for a call which was looking for the 'Next Generation Small UAS' and was funded by the Centre for Defence Enterprise (CDE). The motivation behind the call was:

> "UK Armed Forces need the capability to carry out Intelligence, Surveillance and Reconnaissance (ISR) missions within highly complex environments such as inside buildings and deep within urban canyons."

The funding was for an UAS which can show advances in technology in various areas of interest, of which one of them was to:

> 'Perch-and-stare on the edge of buildings, on window ledges, on telegraph wires, etc'

This highlighted the demand for such systems in a military context [8].

This paper will concentrate on the design and optimisation of a reconfigurable perching element for a VTOL multi-rotor UAV.

1.1 Formulating research questions

An extensive literature search was conducted. The results from the search enabled the formulation of research questions, which would be the dominant guidelines for the designing and optimisation process. This helped gain insight into the topic area as well as highlighting opportunities to contribute new knowledge. This focused the study towards a specific problem within the field of VTOL UAV development which has been identified as the ability to perch onto street furniture, but more specifically onto lighting columns.

1.2 Research questions

The research questions that have been answered in this paper and which were the driving factors for the rest of the research are listed here:

- What factors affect a VTOL UAV's ability to perch?
- What is the most efficient form of perching on existing street furniture?
- What forces are required to sustain a perch under various environmental conditions?

2. LITERATURE REVIEW OF PERCHING AND LANDING SYSTEMS

In order to see what developments have been made in the specific area of landing/perching UAVs, the available literature was investigated and analysed. The developments for landing/perching systems seem to be more heavily leaning towards the autonomous landing of VTOL UAVs, with a few projects looking at perching.

At the University of Illinois, a small flapping UAV, which is lacking vertical tail agility just like birds, is capable of landing/perching on a human hand. The small flapping bird-like UAV is able to work out the best trajectory to execute the perch. It relies on the Vicon™ motion capture system to provide global reference positioning and orientation of the wings and fuselage. The Vicon™ system consists of 16 InfraRed (IR) cameras which track reflective markers attached to the articulated parts of the small flapping wing system. The setup can cost anything from £15k+ depending on the types of cameras and software used [9, 10]. The aim is to execute a perch in the gliding phase of the flight by adjusting the wings and control surfaces like a bird. The 44 g micro air vehicle (MAV, which Paranjape et al are tracking the bird to an accuracy of 1 mm at 100 Hz and controlled by closed-loop proportional-integral-derivative (PID) which is computed at 60 Hz then transmitted at 20 Hz. The disadvantages of this system is it's practicality in outdoor scenarios where without the Vicon™ system tracking and controlling the MAV, it would be useless as all the computation is done off-board [11]. The small flapping wing system brings the knowledge and understanding of how nature's birds achieve perching.

Stalling before perching was also implemented by Cory at Massachusetts Institute of Technology (MIT) where a larger UAV was able to perch on a typical electrical wire. Again using the Vicon™ system, Cory was able to use the flapping wing UAV to stall just before the perch by exploiting pressure drag on its wings and tail, but struggled outdoors [12].

Whilst work is being conducted on the dynamics of the flight for perching manoeuvres, The Computer Science and Artificial Intelligence Lab at MIT are using a similar hook setup to perch onto an electrical power line. Moore and Tedrake detects the magnetic field around the electrical power line using the on-board magnetometers to hone in on the electrical field to execute the perch [2]. This collaboration is ideal as one group at MIT conducts work on the dynamics of the flight and the other team looks into the recognition of the perching site.

At Stanford University's Biomimetics and Dexterous Manipulation Laboratory, Desbiens et al have developed their own bird-like claw which grabs onto outdoor walls. The fixed wing UAV is able to fly straight towards a solid wall before manoeuvring to a vertical stall position with a high attack angle, similar to the MIT system, to slow the UAV down in order to give the claws a chance to grip the wall. The 400 g UAV has an ultrasonic sensor mounted to the front of the fuselage which detects the wall to engage the perching manoeuvre from up to 5 m away. The ballistic motion of the plane contacts the wall between 1-3 m/s where the leg and foot suspension keeps the claw engaged whilst dissipating the kinetic energy from the flight [13]. The disadvantage of this type of system is the UAV platform that is used which is unable of achieving zero velocity, which is crucial to perching. By achieving a state of zero velocity, it allows the UAV to make a more controlled perching manoeuvre. This system also suffers the danger of misjudging the wall surface and risk getting damaged due to crashing head first into a solid wall. They are also limited to the type of wall face they can perch onto, but do have the advantage of having on-board intelligence of conducting the perch without user input. The MIT system which not only relies on external controllers, but also only works indoors, whereas the Stanford system can work in real outdoor scenarios.

Various undercarriage gripper arrangements were also found in the literature which was not directly linked to perching but have shared components to achieve different applications. Not all of them were used for landing/perching purposes. Some were used as manipulators such as Voyles and Jiang's force closure grasping UAV at the University of Denver. This UAV's manipulator was designed to be able to apply torque action such as that found in a wrench using thrust vectoring to achieve the grasp [14]. Although the UAV platform is designed to allow for forced closure grasping, the manipulator is still yet to have intelligence of its own to allow for aerial manipulation.

At the University of Pennsylvania, Lindsey et al are using the under-slung gripper design for an interesting application. They have the gripper system attached to the bottom of a quadrotor UAV flying in a controlled indoor environment, again relying on the Vicon™ camera motion tracking system for navigation and to stack special magnetised building blocks to create pre-programed structures. Each building block is transported individually by a group of UAVs working together on completing the desired structure. The intelligent part is in the algorithm instructing the UAVs in a collaborative manner to complete the task together [15]. The drawback to this system is the accuracy of the Global Positioning System (GPS) which is within a 7.8 m radius worst case and nominally within 4 m accuracy. The horizontal error is less than 3.9 m [16], 95% of the time, which is not accurate enough to enable close quarter UAV collaboration without a mid-air collision. With the launch of the new Galileo satellite constellation in 2016, the accuracy should be within 100 mm [17]. The only advantage to these systems is that they have their own on-board controllers for the actuation of the manipulator.

The indoor aerial gripping quadrotor from Utah State University has the issue that not every graspable item has a recognisable pattern. Ghadiok is using IR Light Emitting Diodes (LEDs) as a marker and using the low cost IR camera from a Nintendo Wii Mote to track the position of the UAV for directional control. The UAV is able to track the IR LEDs at a rate of 200 Hz. Once the UAV is over the object, it then positions itself to grasp the object surrounded by the pre-placed IR LEDs. The camera can track up to 6 LED beams to gain positional information [18].

Ghadiok has understood how aerial grasping should be conducted and highlights three major challenges that need to be overcome:

- Precise positioning of the UAV.
- Object sensing and manipulation.
- Stabilisation in the presence of disturbances.

The interaction between an object and the UAV creates instability in the flight dynamics, which must be dealt with in order to achieve aerial grasping [19]. The system relies on off-board processing which is undesirable as it is not always possible to have an umbilical cord or reliable radio transmission. However they have underlined some key points which will be used when developing the reconfigurable perching element.

Similar to the building block application, Pounds et al at Yale University have used remotely operated helicopters with a gripper underneath the system to carry various payloads to see what the effects will be on the stabilisation during flight [20] and hover with an off-the-shelf autopilot with unmodified PID gains. Whilst the gripping is done under the remote instructions of the pilot, they have acknowledged that there will be disturbances to the aircraft from external forces, whether it is a perching manoeuvre or an aerial manipulation [21]. By understanding the external forces, they estimate the counter-acting forces required to keep a stable flight, but with the input of an expert pilot.

Work on autonomous landing, which is closely related to perching, has also been conducted but relies on recognition of pre-placed patterns or sensors on or around the landing/perching site. At the University of Tübingen in Germany, Wenzel et al have been tracking a ground vehicle which is transmitting an IR beam to the quadrotor UAV, which is similar to the work done at Utah State University as previously mentioned. Intelligent use of low cost sensors and off the shelf components enabled the successful landing of a moving vehicle. Of course it all relies on the placement of the IR transmitter which might be feasible for a moving vehicle but not for an unreachable land/perch site [22]. Roke Manor Research Limited in the south of England is also working on a recognition based landing system. Rather than relying on IR beacons surrounding the land/perch site, they use a smart recognition algorithm to locate and land on the 'H' of a helicopter pad [23].

Doyle et al have been developing 'An Avian-Inspired Passive Mechanism for Quadrotor Perching' which is a passive system capable of maintaining a perch without the need for any additional power. It relies on the mass of the quadrotor to act as a gripping force. Its design adopts the use of an interesting linkage system which exists in the Sorrow bird which allows the mass of the UAV to ensure the platform stays put on the perch site. However, due to the interesting design of the gripper, it easily adapts to most uniform profiles. The flexible finger joints wrap around the perchable cross section for a secure hold. Heavily inspired by nature, the gripper has no electrical parts, which simplify its operation. However, it still relies on the coordinated instructions of the pilot and is also very bulky which overshadows the UAV and affects the flight dynamics [24, 25].

3. PRE-CONCEPT GENERATION

Before concepts were generated, more information was required, such as identifying common features about the perch site, along with further knowledge on grippers.

3.1 Identifying common features

The ideal location to perch on street furniture would be on the projection bracket of the lighting column. But more precisely in-between the lantern unit and the column itself as there would be the least amount of obstructions and this is where the most common feature is (Figure 1). A survey conducted in greater London looking at the different profile types of bracket projections, of which the most common was the circular profile which ranged between 33.5-109 mm diameters. Twenty different types of lighting columns were identified. The median diameter of 42.5 mm sits between the first and third quartile (35-50 mm respectively) (Figure 2). There are however a few outliers which are represented by the un-filled circles, which indicates a group of lighting column which has a projection bracket diameter outside the norm but are still considered. The angle at which the projection bracket exits the main column also varies between 0° to 15°. These projections have regulations which the Highway Agency states that the bracket projection cannot exceed a projection of 0.25 x the nominal height of the lighting column or less than 3 m whichever is the least. The maximum height restrictions for steel, aluminium and concrete lighting columns are <20 m or <18 m with a bracket. Glass fibre lighting columns have considerably greater height restrictions due to the structural rigidity of the glass fibre column. It must be <10 m with a bracket not exceeding 1.5 m [26]. The projection brackets also tend to be angled which does not exceed five degrees.

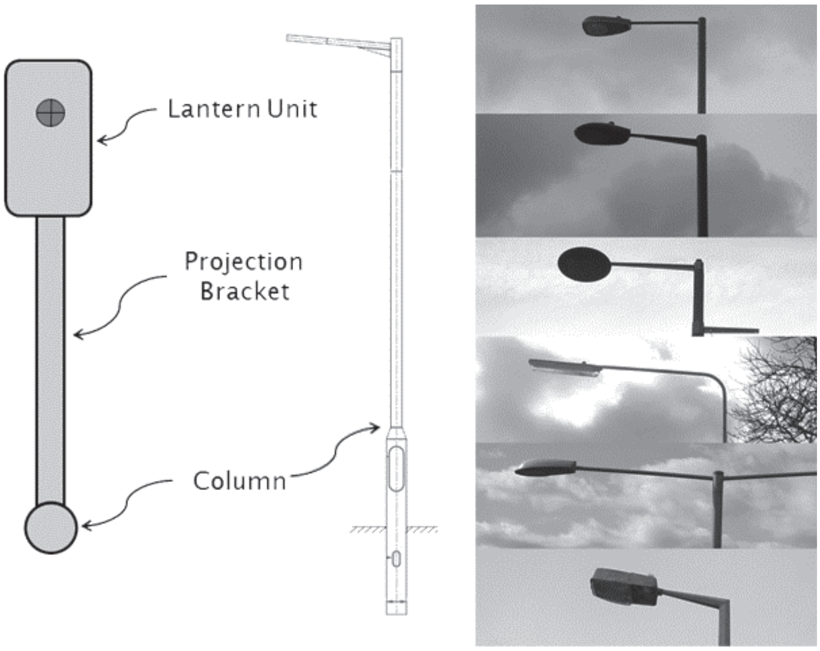


Figure 1. Projection bracket layout and examples from an urban survey.

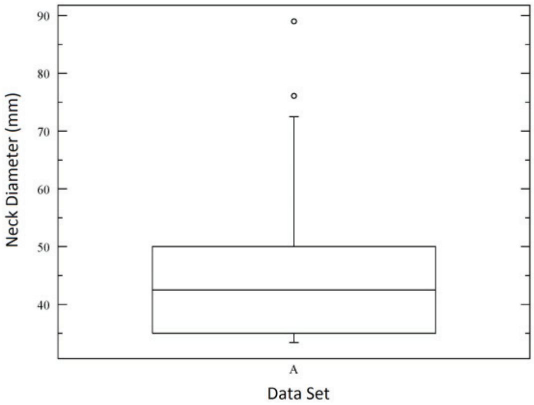


Figure 2. Box plot of projection bracket neck diameter.

3.2 Understanding grippers

Looking to biological inspiration, lighting columns are regularly perched on by birds. Understanding how they achieve a firm grasp was essential. Reviewing mechanical grippers, there were many ways in which a gripper could hold onto the perch site. This physical interaction between the perching element and the projection bracket are considered an active pair mating. Monkman has identified four prehension methods into the following categories: Impactive, Ingressive, Astrictive and Contigutive.

Impactive gripping is when the solid jaw of the gripper touches the objects surface to produce the necessary grasping force. Ingressive gripping is the deformation or intrusion of the surface of the gripping moving into a predefined depth of the object. Astrictive is the attraction between two surfaces through either natural properties or applied elements. Contigutive is interaction between two surfaces. These gripper classifications are broken down further (Table 1) [27].

Table 1. Gripper Classification. Adapted from a table by Monkman (2007).

Prehension Method	Gripper Type	Typical Examples
Impactive	-	Clamps (external fingers, internal fingers, chucks, spring clamps), tongs, (parallel, shear, angle, radial)
Ingressive	Intrusive	Pins, needles, hackles
	Non-intrusive	Hook and loop
Astrictive	Vacuum Suction	Vacuum suction cup/bellow
	Magnetoadhesion	Permanent magnet, electromagnet
	Electroadhesion	Electric field
Contigutive	Thermal	Freezing, melting
	Chemical	Permatack adhesives
	Fluid	Capillary action, surface tension

3.3 Product Design Specification (PDS)

These guidelines were set in order to move on to the next stage; concept generation. The fourteen criteria contain both quantitative and qualitative data sets. The PDS allows the design process to be more efficient as the concepts must stay within the set parameters. With the information gained from the literature search, gripping techniques and perching site, the PDS can be specifically designed to meet the project parameters. The UAV test platform to be used is the MikroKopter (MK) Hexa; a multi-copter which as the name implies has six rotors on the same horizontal plane. At the tip of the equally spaced out arms, which are at 60° from each other, are the brushless out- runner motor with ten inch fixed pitch propeller combination. The advantage over a single rotor helicopter is that it has fewer moving parts and linkages which produce less vibration. It is powered by a 14.8 Vdc lithium-polymer battery which is rated at 3300 mAh. The Hexa weighs

1480 g with the battery and 1105 g without and has a 555 mm pitch circle diameter for the centre of the motor shafts. The Hexa has also been used as a research platform by Winkvist, Peter and Lea-Cox [28-30]. The following are crucial attributes which helped determine the best concept:

- Multi-functional: This category rewarded any system which replaced the existing landing gear and converted it into an all-in-one system (i.e. the designed system replaces the existing 84.4 g landing legs and no longer needs them). Systems which still require the use of the original landing legs or additional support for landing were also be penalised in the mass category.
- Mass: Less than 1 kg including all elements of the landing system (due to the payload capabilities of the MK Hexa).
- Emergency Landing: In the event of a total electronics failure during landing or take-offs, the UAV must be able to land on a flat horizontal surface (i.e. landing gear always in the ready to land position). If the system required additional support for this it will be penalised in the mass category. It rewarded concepts which were ready to land as the landing gear does not have to be initialised.
- Idle/Operational Power: System must not use additional power to keep the landing system holding (i.e. no power consumption during idle state of the system). Research showed that UAVs are already power hungry. Adding more burdens on the system will reduce the UAVs capabilities. UAV has to execute the manoeuvre in a timely manner whilst consuming minimal power. No more than 45 W at 14.8 Vdc which shouldn't impede the endurance of the UAV.
- Environmental conditions: The platform must be able to operate in the following environmental conditions, based on statistics from Met Office UK and Windfinder [31, 32]: -10 to 30°C temperature range. 10 year (2001-2011) average wind speeds in the UK of 4.6 m/s, with wind gusts up to 28 m/s.

- Perchability: All operations must be conducted in a safe manner at all times. If the system were to land below the projection bracket then the chances of survival would be less than if it were to land above the bracket. This is due to there being the column element which can get in the way.
- Centre of Gravity: The perching elements CoG must be close to the centre of the UAV's CoG.
- Complexity: The system must be able to survive the usual wear and tear. It must also be able to withstand the stresses and strains of regular UAV operations (i.e. landing, acceleration in all directions, etc). If the system has more moving parts, then the likelihood of it affecting the flight dynamics are higher.
- Engaging/Disengaging time: The system must be able to engage and disengage in less than 6 s. The longer it takes the more power the UAV will consume. This is considered to be the time taken to initiate the contact and confirm the hold and power down.
- Volume: No bigger than 0.3 m diameter from the centre of the MK Hexa (due to airflow restrictions), and less than 0.2 m height which gives a volume of 0.014 m^3. Data taken from existing landing skids.
- Multi-purpose: This criterion rewarded concepts if it were to have the capability to be used on multiple materials and terrain types.
- Cost: The landing/perching system must cost less than £350, excluding sensors.

These criteria were also used to score each concept against each other on a scale of 0 to 10 in the weighted matrix. The answer to the research question 'What factors affect a VIOL UAV ability to perch?' is presented in the 14 different criteria which when combined highlights the factors which affect the perching capabilities of a VIOL UAV see (Table 2).

4. CONCEPT GENERATION/SELECTION

Concept generation was a very important stage which needed a deeper understanding of the problem in order to solve it in the most efficient way. The main objective was to land onto a lighting column efficiently and effectively in order to preserve battery power whilst surveying an area. It became clear that the system must be able to orientate itself in relation to the lighting column so that is can land every time with the system perfectly lined up with the bracket projection. Also taking into consideration how fast the system must execute the manoeuvre, how much the system will weigh and how much power it will consume whilst executing the task. After several concept generation iterations, 53 concepts were created of which only 21 were taken to the next stage as some concepts were grouped together and/or combined. The task of selecting a final concept would have been difficult without a weighted matrix to guide it.

It is also noted that a pattern emerged regarding the adhesion method. Two of the top five concepts use impactive – clamping method (overall position first and third) for adhesion between the perching element and the projection bracket of the lighting column. Two use astrictive – magnetoadhesion (overall position second and fourth) and the fifth uses contigutive – chemical. A detailed description of each can be found in the section on 'The top five concepts'.

4.1 Weighted matrix

Pahl & Beitz and Black commonly use a weighted matrix approach to evaluate each criterion to select the strongest concept, therefore this method was also used in this research [33, 34]. The top five designs which came out on top after applying the weightings to the concepts are highlighted in (Table 2). Each concept was given a score per criterion, which was multiplied by the criterion weighting. The sums of all the scores for each concept are added up to give a final score. The sum of all the criteria weightings is 100, which are distributed amongst the 14 different criteria.

Prior to giving each concept a score, each criterion had to have a clear useable guide which can easily assign a mark for each aspect of the concept (Figures 3, 5-8).

4.2 Breakdown of the weightings and scores

Some of the following criteria have a quantitative number which can be easily determined or estimated using calculations, where other criteria require a slightly more elaborate approach to give it a score. Middendorf has s done by grouping the design attributes into sets which are given a score (i.e. set 1 will result in a score of 10). The number of sets per criteria, are determined by the number of attributes which can be judged and vary between 2-4 sets. The score of 10 will then be divided into the number

Table 2. Weighted matrix showing the five highlighted concepts which scored the highest. Concepts have been ordered according to rank.[1]

	Weighting	15	15	11	11	9	7	7	5	5	5	5	2	2	1	100	
Concept No.	Concept Name	Multi-functions	Mass	Emergency Landing	Idle Power	Environmental Conditions	Perchability	Centre of Gravity	Complexity	Engaging Time	Disengaging Time	Volume	Operational Power	Multi-purpose	Cost	Total	Gripper Classification
-	Perfect System	10	10	10	10	10	10	10	10	10	10	10	10	10	10	1000	-
-	Worst System	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-
3	The Claw	10	3	10	10	10	10	5	7	8	8	6	6	10	2	789	Impactive - Clamp
5	Magno Screw	5	5	10	10	10	10	10	7	10	5	7	7	5	3	772	Astrictive - Magnetoadhesion
8	Slider	10	2	10	10	10	10	5	7	3	8	6	7	10	4	753	Impactive - Clamp/Tong
4	Magno Hug	10	3	10	10	10	10	5	7	8	3	6	4	5	2	750	Astrictive - Magnetoadhesion
12	Slimer	0	7	10	10	10	10	10	7	10	9	6	6	5	5	742	Contigutive - Chemical
11	The Gecko	0	7	10	10	10	10	10	7	10	3	6	6	5	5	712	Contigutive - Chemical
18	Snap On Cuffs	0	10	10	10	0	10	5	10	9	2	10	10	10	10	680	Impactive - Clamp
19	The Lock Down	0	4	10	10	10	10	10	7	5	9	7	4	5	4	672	Impactive - Clamp
14	The Jumper	0	7	10	10	5	10	10	7	10	3	6	10	0	5	665	Astrictive - Electroadhesion
6	Twister	10	1	10	10	5	10	5	7	1	2	5	4	10	1	639	Impactive - Clamp
7	The Hook	0	10	10	10	0	0	5	10	10	10	10	10	10	10	655	Impactive - Clamp
16	The Winch	0	3	10	10	10	10	10	4	0	8	6	4	5	3	606	Astrictive - Magnetoadhesion
2	The Millipede	10	4	0	0	10	10	10	4	5	5	6	4	10	1	569	Ingressive - Pins
21	Fly	0	4	10	10	0	10	10	10	2	3	7	3	5	3	549	Contigutive - Fluid
13	Tesla Grip	0	3	10	0	5	10	10	7	10	10	6	1	0	5	512	Astrictive - Electroadhesion
1	The Balloon	10	1	0	0	10	10	5	7	2	10	4	1	10	2	499	Astrictive - Vacuum Suction
20	Freezo	0	4	10	0	10	10	10	10	2	0	7	1	5	0	507	Contigutive - Thermal
10	Bat Feet	0	10	0	10	0	0	5	10	10	1	9	10	10	10	495	Impactive - Clamp
15	Shooting Gripper	0	1	10	10	10	10	0	0	0	8	4	1	10	1	478	Impactive - Clamp
9	Sucker	0	2	10	0	5	10	10	7	3	4	7	1	10	5	457	Astrictive - Vacuum Suction
17	Monkey Tail	0	3	0	0	10	10	5	4	1	5	8	2	10	1	355	Impactive - Clamp

---

[1] See: http://blog.soton.ac.uk/robotics/files/2013/07/Appendix-A.pdf for all sketches of all design concepts.

of sets available (i.e. two sets will have a score of 10 and 0 for sets 1 and 2 respectively). Each criterion was optimised to ensure the systematic approach which has been adopted for this research [35]. Unfortunately no other research group have conducted a similar approach to landing gear design let alone perching.

Emphasis on the importance of the multi-functionality was given by assigning the highest weighting along with mass as these two criteria have the greatest affect on the UAV.

The percentage of the weightings for each criterion was as follows:

- Multi-functional 15%
- Mass 15%
- Emergency Landing 11%
- Idle Power 11%
- Environmental Conditions 9%
- Perchability 7%
- Centre of Gravity 7%
- Complexity 5%
- Engaging Time 5%
- Disengaging Time 5%
- Volume 5%
- Operational Power 2%
- Multi-purpose 2%
- Cost 1%

4.2.1 Multi-functional

This criterion has the joint highest weighting and was considered to be one of the most important attribute to the generated concepts. Weighted at 15%, this criterion had three sets which are marked as 10, 5 & 0 for sets 1, 2 & 3 respectively. The aim here is to reward any system which replaced the existing landing system as described previously in the PDS section. This multi- functional attribute was very desirable as it saved on mass and increased usability. Concepts must be able to increase the existing capabilities of the landing gear and/or outperform it.

4.2.2 Mass

Mass has always been an important factor with every type of manned or unmanned system. By increasing the perching capability of a UAV through reconfiguration, it must have very minimal if not any impact on other properties which affected the UAVs flight capability. This quantitative criterion exponentially deterred the concepts from having a larger mass which is why it was given the highest weighting of 15%. The MK Hexa has a payload capability of 1 kg which was the limiting factor when assigning a score for each concept. Everything below 1 kg was favoured and is exponentially graded to encourage mass loss in the concept, which a linear approach would not do. Using this model, a system which has a mass of 200 g received a score of five, whereas on a linear scale it would receive an eight (Figure 3).

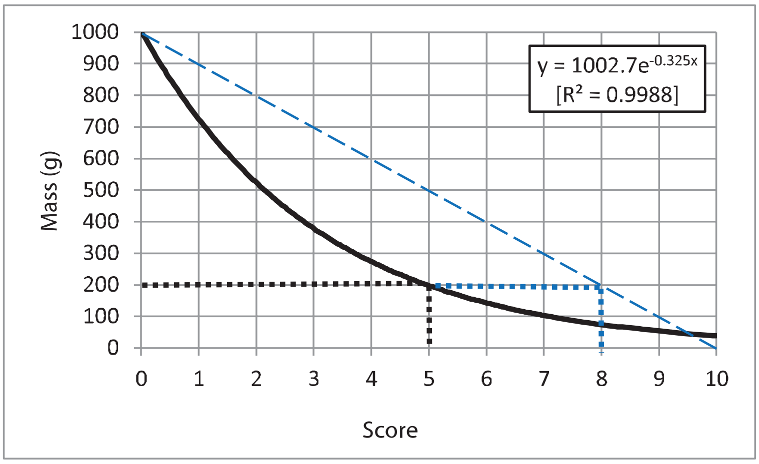


Figure 3. Mass vs. score. Line indicating 200 g would equate to a score of five.

4.2.3 Emergency Landing

Standard landing gear which are found on small man portable VTOL UAVs are either typical helicopter skis or multi-point contact legs (Figure 4). These setups are a passive system which provides a stable method of landing in a controlled manner. They also provide a means of landing in an emergency situation e.g. loss of power at a reasonably low altitude, which cannot be achieved with a landing gear which needs to be activated in order to land i.e. retractable syste m. This criterion emphasised the need that a landing gear must be ready for any type of landing scenarios which the pilot or autopilot cannot foresee therefore given a weighting of 11%. The scoring used a linear scale which split the score into sets 1 and 2 scoring 10 and 0 respectively, which determined whether the concept can or cannot land in such situations.

Figure 4. Landing gear types. (Left) multi point, (Right) skids.

4.2.4 Idle Power

Scoring either a 10 or a 0 for sets 1 or 2, this criterion had a simple grading which determined if the system required a constant supply of power to sustain the hold onto the perch site. Considered to be equally important as ‘emergency landing’ and therefore given the same weighting of 11%.

4.2.5 Environmental conditions

Being able to sustain a hold during any weather condition was another requirement if this perching system is to be used in the real world. This criterion split into three sets which graded the concepts 10, 5 or 0 depending on how well it can hold on during high wind gusts. Set 1 scoring was given to concepts which were not affected by any weather conditions where set 3 would was for concepts affected by the slightest breeze. A weighting of 9% was given to this criterion as a system which cannot hold onto the perch site, would very likely be damaged if blown off by wind gusts therefore falls into the top five for importance. This was the only criterion which was un-controllable and had an infinite number of variables, where other criteria could be manipulated to meet the PDS requirements.

4.2.6 Perchability

Linked with the previous criterion, perchability also looked out for the UAVs survivability. Approaching the perch site from above (set 1) has no obstructions which may get in the way during perching, whereas an approach from below (set 2) has the lighting column itself in the way which can potentially cause problems especially if the weather conditions are windy. A weighting of 7% was applied to this criterion.

4.2.7 Centre of Gravity

VTOL UAVs best operate when the CoG is in the centre of the horizontal plane (set 1). A CoG which is central to all axes ensures that all propulsion systems are working equally and that power is distributed equally. Having a perching system which disturbs the CoG is very undesirable (set 3) and can lead to unwanted fight regimes. This criterion has three sets, which has a grading of 10, 5 and 0 which applied to sets 1-3 respectively. It was also considered to be as important as perchability, therefore given a weighting of 7%.

4.2.8 Complexity

Having a system which can perform a perching manoeuvre with fewer moving parts is more desirable, as it can have a longer operational life, lower maintenance and cheaper to produce. It also may be considered to be more reliable, as its operation becomes less complex therefore given a weighting of 5%. This criterion with four sets determined how the moving parts are assessed. Scoring 10, 7, 4 and 0 the concepts with no moving parts were given the highest score of 10 and the most complex moving part concepts were given a zero.

4.2.9 Engaging/Disengaging time

The criteria for time taken to achieve the hold and release actions were given the same weighting of 5% as they were equally as important to each other. They both have an exponential scoring system, which as mentioned before, encouraged concepts to complete the task quicker than 6 s see (Figure 5). Engaging and disengaging both use quantitative scoring and also share the same scoring graph. The longer it takes for the UAV to achieve the hold, the more likely it is to get blown off course, therefore similarly to mass it is heavily punished the longer it take to execute the perch.

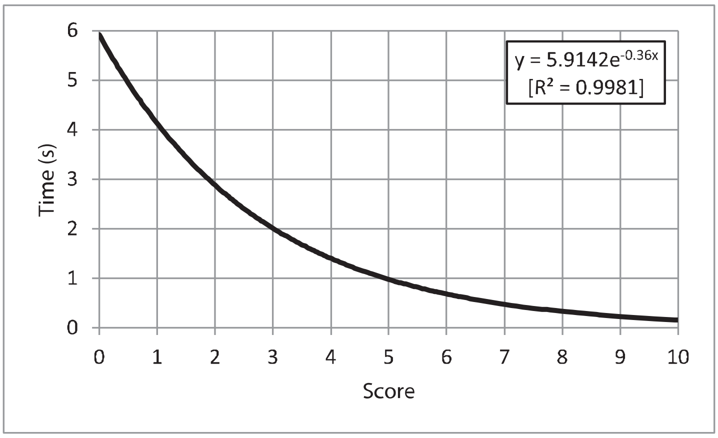


Figure 5. Engaging/disengaging time vs. score.

4.2.10 Volume

This criterion was also given a weighting of 5%, but used a linear scale for the quantitative scoring (Figure 6). The size of the original landing skis fits within the central part of the UAV and in no way was in the prop wash. The aim here was to fit within the central UAV control board and keep clear of the prop wash. For the MK Hexa, this size is 0.3 m diameter and 0.2 m height making a volume of 0.014 m^3. A concept with a volume less than 0.014 m^3 received a score of five or more.

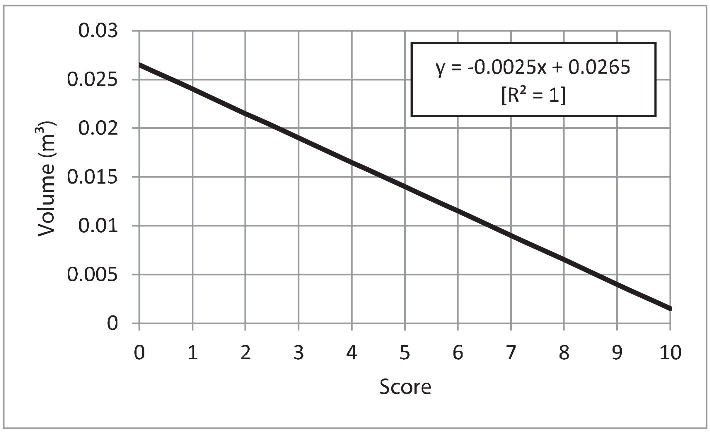


Figure 6. Volume vs. score.

4.2.11 Operational Power

As the actual operational time of the actuations should be less than 6 s, the operational power, if any, would not have little impact on the overall runtime of the UAV. This is criterion is closely linked with engaging time as the longer it takes to execute the perch the more power it will use in. Therefore this criterion was not considered to be the most important and is reflected in the weighting score of 2%, but still important enough to have an exponential scoring to encourage low power usage see (Figure 7).

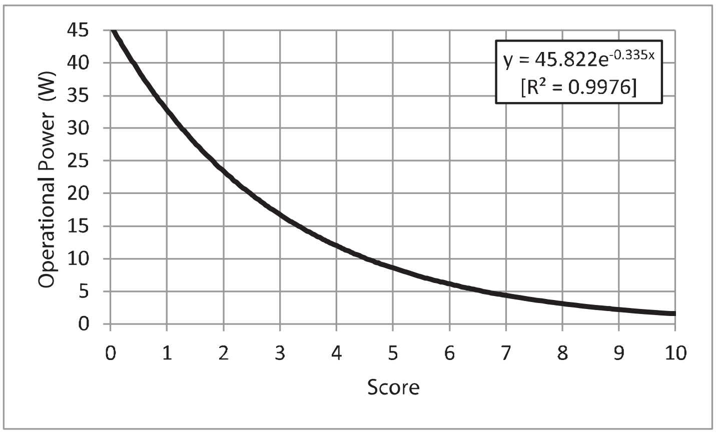


Figure 7. Operational power vs. score.

4.2.12 Multi-purpose

This category highlighted whether the concept was limited to a certain type of material or terrain. Although the perch site had been determined to be a projection bracket of a lighting column, it is still a desirable aspect to have an option of landing on multiple surface types and materials. With a weighting of 2% it is one of the least important aspects which was split into three sets where set 1 would be capable of perching on more than one type of terrain and various material. Set 2 would be capable of perching on more than one type of terrain or material and finally set 3, where the concept can only perch on one type of terrain or material.

4.2.13 Cost

The least important criterion with a weighting of 1%, had minimal effect as it should not be a major driving point which could suppress the creativity of the concept. A sensible budget of £350 will be assigned to just the materials and actuators of the gripper and any required fixtures. This final criterion is also given an exponential scoring system which encouraged interesting concepts with minimal complexity (Figure 8).

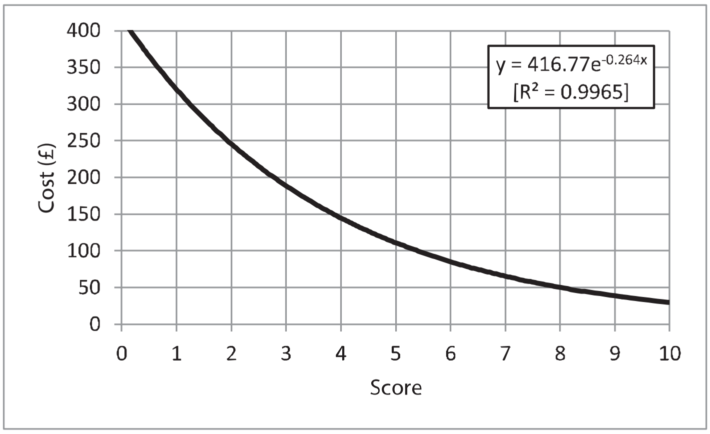


Figure 8. Cost vs. score.

4.3 The top 5 concepts

Looking at (Table 2), the five concepts which had the highest score were taken to the next stage of development. A physical model was made for each concept, as it would give greater understanding as to how each model would work. This also allowed the mechanical principles to be tested out see (Figure 9).

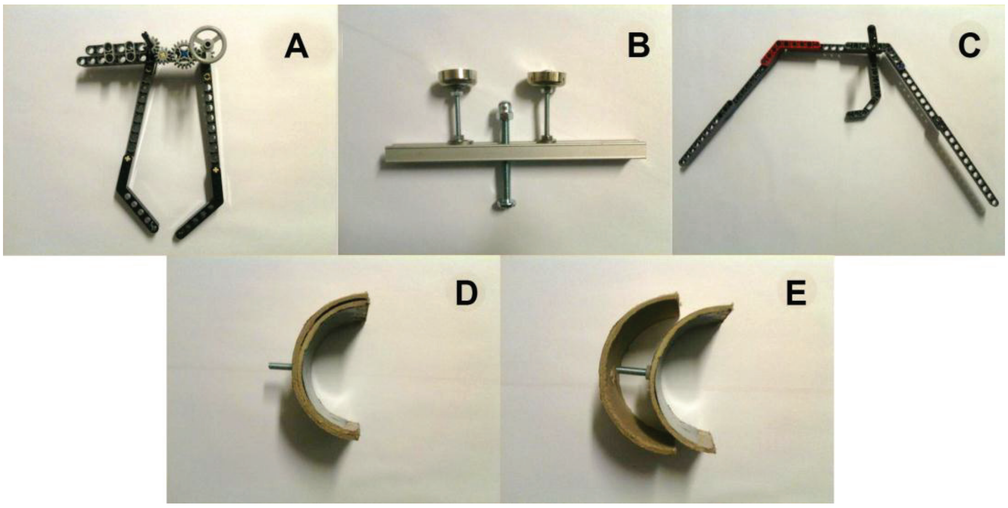


Figure 9. Top five gripper concepts. (A) The Claw and Magno Hub; (B) Magno Screw; (C) Slider; (D) Slimer in loaded position; (E) Slimer in released position.

Image 9(A) represents Concepts 3 and 4 as indicated in the top left-hand side (The Claw and Magno Hug) which have similar construction and geometry but different gripping methods. Image 9(B) shows the workings of Concept number 5 - Magno Screw. It uses a central screw to disengage from the projection bracket. Image 9(C) is Concept number 8 – Slider, which as the name implies it slides down onto the projection bracket to help with the location. Images 9(D) and 9(E) which are located at the bottom represent the Slimer concept, which is Concept number 12 on the concept generation scale. D and E show the perching element in both engaged and disengaged states as the main functionality of this concept was to have a leave behind component.

5. CONCEPT SELECTION

As Concept 3 (The Claw) gained the highest score in the weighted matrix, the modelling was taken to the next stage using a SolidWorks Computer Aided Design (CAD) model. Before a CAD model was created, a more detailed prototype was made in order to understand how the assembly would be done and how it would interact with the projection bracket (Figure 10).

Figure 10. The claw design model gripping the projection bracket.

The Claw, with a score of 789 out of a possible 1000 was chosen to move forward with its development. In order to improve this score, close attention was paid to the criteria in which it could have scored higher. Concepts which had a higher score in those categories were examined for inspiration. The Claw originally had straight legs which wouldn't allow the grasping of larger diameters. The hooking design of the 'Slider' (Figure 9C) was implemented onto the end of each leg which enables The Claw to grasp larger diameters and also aids in self aligning of the legs onto the projection bracket.

5.1 Working prototype

With the mass of the UAV determined, the mass of the perching element estimated and using the approximate wind speeds of the UK, the estimated forces the perching element required were calculated. The mass of the UAV and perching element worked out to be approximately 1.5 kg and the wind speed used to work out the disturbance forces was 4.6 m/s as this is the average value for wind in the UK according to Met Office UK, Windfinder and Ordnance Survey [31, 32, 36].

5.2 Initial model

The initial model was created based on the original concept sketches. Difficulties with the gear mesh between the motor bevel gear and the non-backdrivable screw thread were encountered. The perpendicular setup of the motor to the non-backdrivable screw thread (Figure 11) had problems. This configuration allowed the bevel gear to slip and was un-able to provide the required forces to hold the gripper in a hold stance. This was partly to do with the materials used for the prototype along with the lack of support for the motor bracket and the pitch of the non-backdrivable screw thread. According to Controzzi, the use of this type of screw thread was to ensure that once the grip is accomplished, the motor and screw thread will be able to hold the grip without being driven back (non-backdrivable) [37]. To improve the grip and reduce slippage, a different configuration was used.

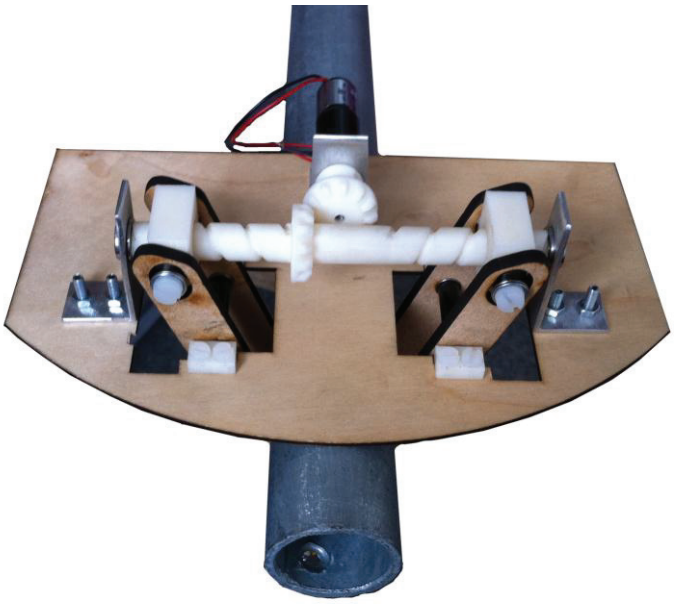


Figure 11. Original design showing bevel gear used for power transfer. (Prototype showing one half of the design only)

As can be seen in (Figure 12) the motors were placed in parallel to the non-backdrivable screw thread. The pitch on the screw thread was also decreased from 10 mm to 5 mm to ensure a better non-backdriving action. As the motor drives the perching element's legs into the projection bracket, the tension between the symmetrically moving screw blocks and the screw thread would ensure the hold to be tight and not loosen when power is cut to the motors. With a more reliable design, calculations were made to work out what properties the motors require in order to hold the UAV in place during 4.6 m/s wind speeds with a leeway for high wind gusts.

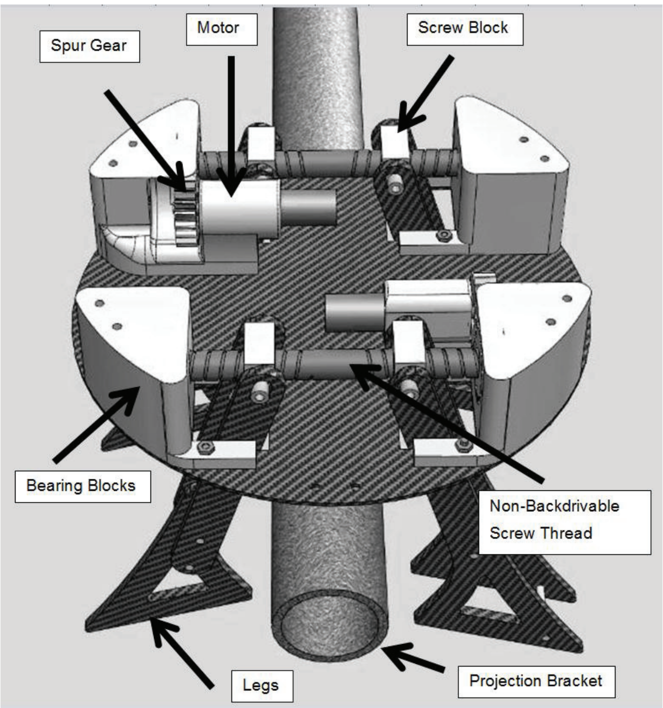


Figure 12. CAD image of the perching concept ‘The Claw’.

5.2 Motor selection

To determine the motors which will be used to drive the gripping mechanism, the forces acting on the UAV must be calculated. The factors which affect the UAVs ability to sustain the hold are wind speeds, size of projected area which the wind blows against, gravity, drag coefficients, mass, density of air, resistive forces between the interacting surfaces and leverage gains. Due to the non- uniform problem produced by this kind of system, some parameters had to be estimated. In most cases the numbers used are the worst case scenarios. This way the gripper can be prepared for normal operational conditions along with more extreme situations.

First the drag forces acting on the UAV were calculated using eqn (1):

$$F_d = \frac{1}{2}\rho v^2 A C_d \tag{1}$$

Where:
Fd = Force drag = Force against the projected surface of the UAV (N)
ρ = Density of air (kg/m^3)
A = Projected area of object which air is blowing against (m^2)
v = Wind Speed (m/s)
C_d = Drag coefficient (dimensionless)

Using 4.6 m/s for v as it is the wind speeds at 10 m, the force acting on the UAV now creates a turning force due to the wind eqn (2) and due to its mass eqn (3):

$$\mathrm{T} = \mathrm{r}F_d \tag{2}$$

$$F_d = ma \tag{3}$$

Where:
T = Turning moment (Nm)
ρ = Radius (m)
F_d = Drag force (N)
m = Mass (kg)
a = Acceleration (m/s^2)

The force which the gripper legs must exert onto the projection bracket is 0.92 N to stay on the bracket projection at 4.6 m/s, which answers the research question: What forces are required to sustain a perch under various environmental conditions? 2.32 N is required for wind gusts up to 28 m/s. To work out the resistive forces between the gripper and the projection bracket eqn (4) is used:

$$F_r = \frac{Fr}{N} \tag{4}$$

Where:
fr = coefficient of friction (dimensionless)
Fr = Resistive forces (N)
N = Perpendicular force (N)

Using a value of 0.75 [38] for the coefficient of friction between steel and rubber, this is what the gripper finger will be lined with, which is the mid value for static hold. The force required to hold the UAV in place at the given parameters is 0.69 N.

The contact point and the point of actuation has a leverage affect which when using eqn (5), the force is 0.65 N.

$$F_e = F_l \frac{d_l}{d_e} \tag{5}$$

Where:
F_e = Effort force (N)
F_l = Load force (N)
d_l = Distance of load to pivot point (m)
d_e = Distance of effort to pivot point (m)

Now that the force at the non-backdrivable lead thread has been determined, this force has to be converted using eqn (6) to work out the torque of the motor required.

$$F_u = Ftan(\alpha + \rho) \tag{6}$$

Where:
F_u = Torque (Nm)
F = Linear force (N)
α = Angle of thread pitch (deg)
ρ = Coefficient of friction

In this case the coefficient of friction is the 3D printed parts contacting the surface of other 3 D printed parts (Acrylonitrile Butadiene Styrene (ABS) onto ABS 0.35). Using eqns (1-6), the required torque of the motor is calculated to be 0.12 Nm.

5.3 Motor testing

With an approximate idea of how the motors must operate, a Maxon motor was selected. A motor test was conducted to confirm the specification of the acquired motor see (Figure 13). The results in (Table 3) proved that the RE-max motor model: 221012 with a 10:1 planetary gearbox would be appropriate for the task. The Maxon motor has torque constant of 0.11 Nm/A and a stall current of 4.25 A which equates to a stall torque of 0.463 Nm.

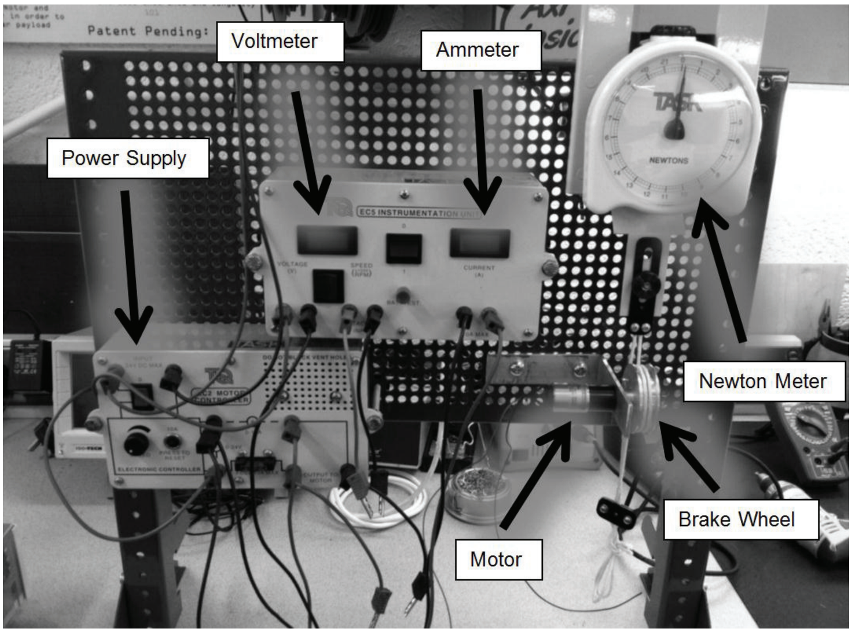
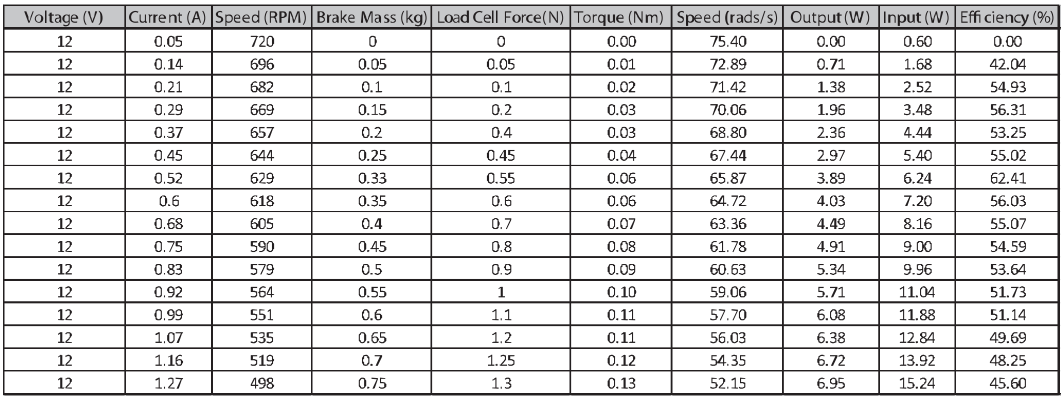


Figure 13. Motor torque testing rig.

Table 3. Motor torque testing results.



Voltage (V)	Current (A)	Speed (RPM)	Brake Mass (kg)	Load Cell Force(N)	Torque (Nm)	Speed (rads/s)	Output (W)	Input (W)	Efficiency (%)
12	0.05	720	0	0	0.00	75.40	0.00	0.60	0.00
12	0.14	696	0.05	0.05	0.01	72.89	0.71	1.68	42.04
12	0.21	682	0.1	0.1	0.02	71.42	1.38	2.52	54.93
12	0.29	669	0.15	0.2	0.03	70.06	1.96	3.48	56.31
12	0.37	657	0.2	0.4	0.03	68.80	2.36	4.44	53.25
12	0.45	644	0.25	0.45	0.04	67.44	2.97	5.40	55.02
12	0.52	629	0.33	0.55	0.06	65.87	3.89	6.24	62.41
12	0.6	618	0.35	0.6	0.06	64.72	4.03	7.20	56.03
12	0.68	605	0.4	0.7	0.07	63.36	4.49	8.16	55.07
12	0.75	590	0.45	0.8	0.08	61.78	4.91	9.00	54.59
12	0.83	579	0.5	0.9	0.09	60.63	5.34	9.96	53.64
12	0.92	564	0.55	1	0.10	59.06	5.71	11.04	51.73
12	0.99	551	0.6	1.1	0.11	57.70	6.08	11.88	51.14
12	1.07	535	0.65	1.2	0.11	56.03	6.38	12.84	49.69
12	1.16	519	0.7	1.25	0.12	54.35	6.72	13.92	48.25
12	1.27	498	0.75	1.3	0.13	52.15	6.95	15.24	45.60

6. GRIPPER REVIEW

Materials typically used in the construction of UAVs are lightweight yet strong. Carbon Fibre is very popular as it is also used in the automotive motorsport industry as it has outstanding properties under high levels of stress. There are various different composites used to construct the gripper. The base plate and top plates were made out of 1.5 mm thick pre-impregnated carbon fibre sheet which was cut out using a water jet cutting machine. The legs were cut using the same method but out of 4 mm foam cored carbon fibre. The advantages of using foam cored carbon fibre were that whilst maintaining a light weight construction, it was also thick enough to have the appropriate support when gripping. By removing the foam core at the interacting point along the legs, a section of rubber was inserted to aid the hold when the gripper closes. The non- backdrivable screw thread, driving blocks and bearing blocks were all printed out on a 3D rapid prototyping machine using ABS plastic. (Figure 14) highlights the labels for the parts with (Figure 15) showing the fully assembled gripper.

The final prototype mass was 420 g with an engaging and disengaging time of 0.5 s, which validated the scoring of the weighted matrix. Due to its independent control of each claw unit, the gripper can also grasp projection brackets with varied taper. The various angles the projection bracket may have should be overcome as the tighter the gripper gasps, it should self-align the UAV to the projection bracket.

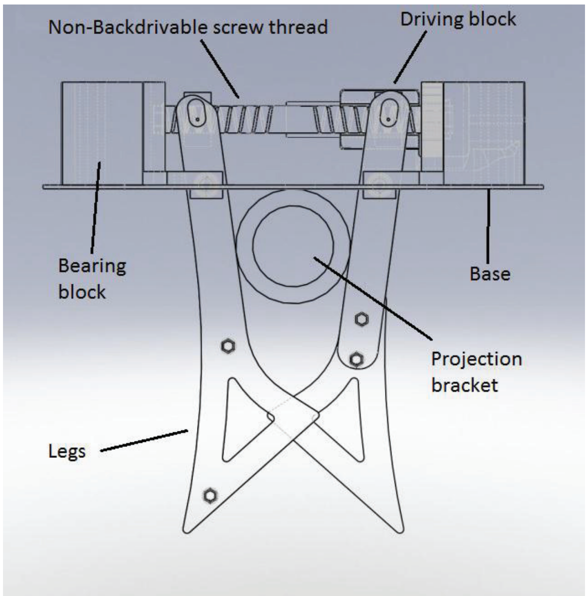


Figure 14. Cross-sectional view of 'The Claw'.

Now that the physical model has been made, looking at the weighted matrix, the new score which The Claw has achieved is 795.3. Some criteria such as cost, volume and operational power have increase as these aspects were slightly out, where engaging and disengaging times have decreased. Weighing in at 420g, the perching system equates to about 22 % of the total UAV mass which decreases the 35 minute endurance to 25 minutes. A surveillance mission usually entails hovering and staring, this wouldn't be much of an issue as it can perch to save on endurance time.

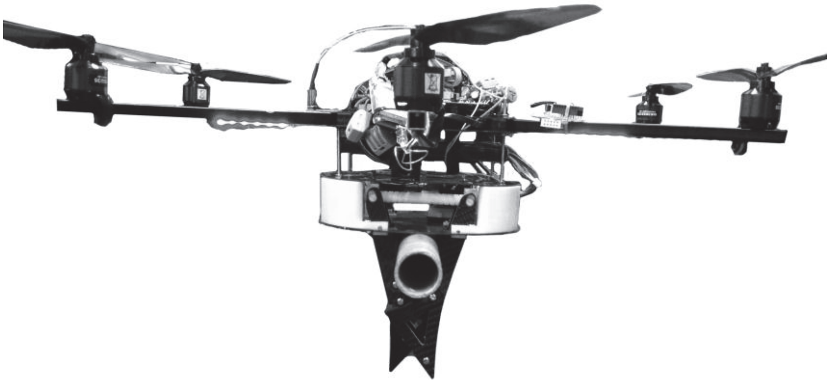


Figure 15. Fully assembled gripping prototype on projection bracket.

6.1 Anticipated Results

The MikroKopter Hexa has capabilities such as altitude hold with approximately 10 cm deviation depending on wind condition. The initial testing will be conducted within a laboratory therefore eliminating any large deviations. The controls of the Hexa will have to be tuned to refine its movement to ensure that the UAV doesn't sway and cause problems when trying to perch. The greatest problem envisaged is any collision during perching caused by any external forces which the UAV may experiences such as getting its legs caught on the projection bracket whilst perching. To avoid this, the alignment just before perching should be doubled checked with alternative sensors such as pencil beam ultrasonic, which can measure the position of the projection bracket.

7. CONCLUSION

Recent attempts to develop perching UAVs make use of the Vicon™ system for accurate positional control. This technology is currently unable to be used in the real-world and therefore is of limited use. The design optimisation process has demonstrated that a reconfigurable perching element can be designed to perch on a range of different sized projection brackets currently found in the urban environment, which truly demonstrates the reconfigurable aspect of this chosen concept (Figure 16). The design optimisation methodology, involving a weighted matrix approach, has led to the creation of a novel gripper, which can perch onto existing street furniture. This method has been validated with a working prototype, which scored highest overall, gaining approximately 2% more than the nearest alternative. The top of a lighting column which holds the luminaire unit on the end of a projection bracket was found to be an ideal location for surveillance UAVs to be able to perch to conduct extended surveillance and reconnaissance missions.

Research questions which were answered in this paper are:

- What factors affect a VTOL UAV's ability to perch?
  - 14 criteria have been identified and are found in the PDS. (Section 3.3).
- What is the most efficient form of perching on existing street furniture?
  - Top approach, impactive clamp with a non-backdrivable latching mechanism.'The Claw'
- What forces are required to sustain a perch under various environmental conditions?
  - The calculated forces for a UAV and perching system that has a combined mass of 1.5 kg in 4.6 m/s wind speeds is 0.15 N and 2.33 N at 28 m/s wind gusts.

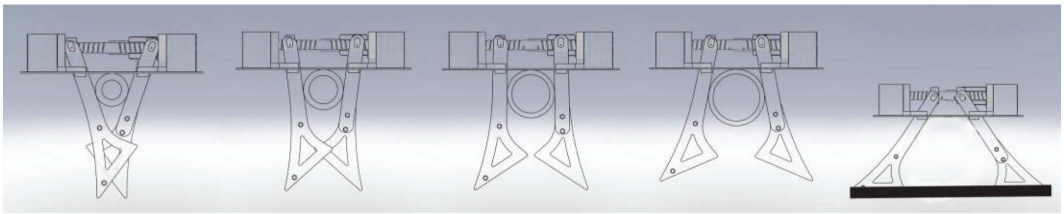


Figure 16. Demonstrating the reconfigurable aspect of the gripper (side profile).

The multi-functionality of the design has been proven with its ability to replace the existing landing gear as can be seen in (Figure 17) in its landing stance. The mass target has also been met, weighing in at 420 g, which was the predicted mass. By utilising a non-backdrivable screw thread design for the actuation, the scores given to the emergency landing and idle power criteria have been justified. 'The Claw' is always in a ready to land stance and only initiates the gripper when required to land on a projection bracket. As it doesn't require any additional power to sustain the grip, it was rewarded the highest score in the idle power criterion. Its low profile and compactness ensures it is not affected by environmental conditions, such as wind. Also this design has little effect on the overall system's CoG. The mechanical design consists of levers, gears and screw thread mechanisms, which keeps the complexity down with minimal moving parts. As the UAV approaches the perch site from above, it also meets this requirement which was set in the PDS. It's fast engaging and disengaging time of half a second is a desirable capability as it ensures a rapid attachment without wasting any unnecessary endurance time.

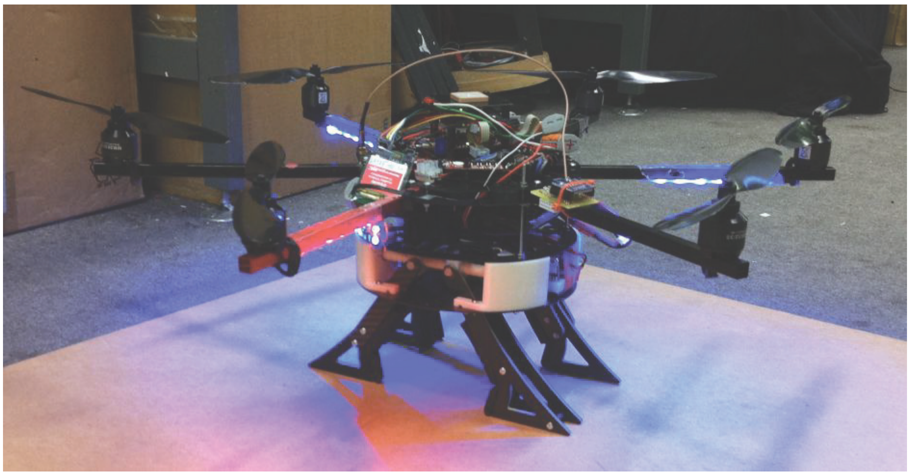


Figure 17. Gripper attached to UAV platform in a landed position.

The leg design allows each leg to hyper-contract into the other leg without colliding and preventing a tight grip as can be seen in (Figure 12, 14-16). This three finger approach was adopted from nature's bird claw designs.

7.1 Further Work

The perching element will be taken to the next stage of development via controlling the UAV to transition onto the perch site from a known start position. This work consists of finalising the design of a test rig, which will allow the UAV platform to transition freely onto the projection bracket. Before achieving the transitioning manoeuvres, control hardware followed by software must be implemented. The transition procedure will allow for each aspect of the perch to be fully tested and developed before moving onto the fully combined perching manoeuvre from a known start position to the projection bracket.

ACKNOWLEDGEMENTS

The authors would like to thank the University of Southampton for providing the workspace and facilities which made this project come to life. Also the ASL and Skunkworks team have been very helpful.

REFERENCES

[1] QinetiQ. Breakthrough unmanned aerial surveillance technology. 2008; [Online] http://www.qinetiq.com/what/products/Documents/Zephyr-UAV.pdf, Accessed Date: April2013

[2] Moore J, Tedrake R. Powerline Perching with a Fixed-Wing UAV. *American Institute of Aeronautics and Astronautics*. 2009.

[3] UAVforge. Competition Course. 2011; [Online] http://www.uavforge.net/instructions.php, Accessed Date: April 2013

[4] Langkamp DS. Quadrotor Flight Performance [PhD Thesis]: University of Manchester; 2011. [5] Cetinsoy E, Dikyar S, Hancer C, Oner KT, Sirimoglu E, Unel M, et al. *Design and construction of a novel quad tilt-wing UAV. Mechatronics*. 2012; 22: 723-45.

[6] Prior S, Shen ST, Erbil MA, Brazinskas M, Mielniczek W. Winning the DARPA UAVForge Challenge 2012 – Team HALO. *Unmanned Systems*. 2013; 1: Special Issue [In Press].

[7] Page L. DARPA seeks 'perch and stare' spy-fly robot. Blasted robot bats on the washing line again. 2008; [Online] http://www.theregister.co.uk/2008/08/21/darpa_gargoyle_mode/print.html, Accessed Date: Nov 2012

[8] MoD. Next Generation Small UAS. In: DSTL, editor.: MoD; 2011. p. 7.

[9] Muir A. What do you want from motion capture? 2011; [Online] http://diydrones.com/profiles/blogs/what-do-you-want-from-motion-capture, Accessed Date: April 2013

[10] PEPPM. Official Vendor Line-Item Price Submission Form - VICON. 2013; [Online] http://www.peppm.org/Products/vicon/price.pdf, Accessed Date: April 2013

[11] Paranjape A, Kim J, Chung S-J. Closed-Loop Perching of Aerial Robots with Articulated Flapping Wings. *Robotics*. 2012; Under Review.

[12] Cory RE. Supermaneuverable Perching [PhD Thesis]. Massachusetts: MIT - *Massachusetts Institute of Technology*; 2010.

[13] Desbiens AL, Asbeck AT, Cutkosky MR. Scansorial Landing and Perching. *Springer Berlin Heidelberg*; 2009. p. 169-84.

[14] Voyles R, Jiang G. Hexrotor UAV Platform Enabling Dextrous Interaction with Structures - Preliminary Work. *Safety, Security, and Rescue Robotics* (SSRR). Texas. 2012.

[15] Lindsey Q, Mellinger D, Kumar V. Construction with quadrotor teams. *Autonomous Robots*. 2012: 13.

[16] Hughes WJ. Global Positioning System (GPS) Standard Positioning Service (SPS) Performance Analysis Report. 2013; [Online] http://www.nstb.tc.faa.gov/reports/PAN80_0113.pdf, *Accessed Report* 80

[17] Thomas M. Euro GPS 'accurate to below 10cm'. 2011; [Online] http://news.bbc.co.uk/today/hi/today/newsid_9620000/9620148.stm, Accessed Date: April 2013

[18] Ghadiok V. Autonomous Aerial Manipulation Using a Quadrotor [Master of Sciences]: *Utah State University*; 2011.

[19] Ghadiok V, Goldin J, Ren W. Autonomous Indoor Aerial Gripping Using a Quadrotor. Intelligent Robots and Systems. San Francisco, CA, USA. *IEEE*; 2011. p. 4645-51.

[20] Pounds PEI, Bersak DR, Dollar AM. Grasping From the Air: Hovering Capture and Load Stability. IEEE International Conference on Robotics and Automation. Shanghai International Conference Centre, China. *Intech*; 2011. p. 2491-8.

[21] Pounds PEI, Dollar AM. Hovering Stability of helicopters with Elastic Constraints. Systems and Control Conference. Cambridge, Massachusetts, USA. *ASME*; 2010. p. 781-8.

[22] Wenzel KE, Rosset P, Zell A. Low-Cost Visual Tracking of a Landing Place and Hovering Flight Control with a Microcontroller. *J Intell Robot Syst*. 2010; 57: 297-311.

[23] Whitehouse R. Autoland. 2010; [Online] http://www.roke.co.uk/resources/datasheets/0373-Autoland.pdf, Accessed Date: Nov 2012

[24] Doyle CE, Bird JJ, Isom TA, Kallman JC. Avian-Inspired Passive Perching Mechanism for Robotic Rotorcraft. Intelligent Robots and Systems. San Francisco, *CA*, USA. 2011. p. 4975-80.

[25] Doyle CE, Bird JJ, Isom TA, Kallman JC, Bareiss DF. An Avian-Inspired Passive Mechanism for Quadrotor Perching. *Mechatronics*. 2012; 18: 506-17.

[26] Highways Agency. Design of Lighting Columns: Highway structures: Design (substructures and special structures), materials. 2004; [Online] Accessed

[27] Monkman GJ, Hesse S, Steinmann R, Schunk H. Robot Grippers. Weinheim: Wiley-VCH; 2006.

[28] Winkvist S, Rushforth E. Towards an autonomous indoor aerial inspection vehicle. Industrial Robot: *An International Journal*. 2013; 40: 196-207.

[29] Peter P. Implementing an unmanned aerial vehicle (UAV) for surveillance tasks [Bachelor Thesis]: Saarland University; 2012.

[30] Lea-Cox JD, Belayneh B, Kim J, Majsztrik C. The Value of Weather Data for Daily Nursery Management Decisions. In: Bachman G, editor. Engineering, Structures and Innovations. Arthur R. Outlaw Convention Centre, Mobile, AL, USA: *Southern Nursery Association*; 2012. p. 86-98.

[31] Windfinder.com. Windfinder - Wind & weather statistic London City Airport. Online wind statistics 2012; [Online] http://www.windfinder.com/windstats/windstatistic_london_city_airport.htm, Accessed Date: Nov 2012

[32] Met Office. Energy trends section 7: weather; Average Wind Speed and Deviations from the Long Term Mean. 2013; [Online] https://www.gov.uk/government/statistical-data- sets/december-2012-energy-trends-weather-data, Accessed Date: April 2013

[33] Black R. Idea Evaluation. Design and Manufacture: An Integrated Approach: Macmillan Pub Ltd; 1996. p. 108-11.

[34] Pahl G, Beitz W, Schulz H-J, Jarecki U. Selection and Evaluation Methods. Engineering Design: A Systematic Approach: *Springer*; 2007. p. 106-24.

[35] Middendorf WH. Optimum Design. Design of devices and systems: M. Dekker; 1986. p. 324-8.

[36] Ordnance Survey. Wind statistics for POSTCODE: WC2N. 2012; [Online] http://www.shop.ordnancesurveyleisure.co.uk/search/series/wc2n/1, Accessed Date: Nov 2012

[37] Controzzi M, Cipriani C, Carrozza MC. Miniaturized non-back-drivable mechanism for robotic applications. *Mechanism and Machine Theory*. 2010; 45: 1395-406.

[38] Fenske G, Erck R, Ajayi L, Erdemir A, Eryilmaz O. Parasitic Energy Loss Mechanisms Impact on Vehicle System Efficiency. 2006; [Online] http://www.diracdelta.co.uk/science/source/f/r/friction/source.html#.UWmHjLUqZLh, Accessed Date: Nov 2013