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LA . A el Le elin Landin Plat o m o A tonomo s Miniat e A s

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Abstract **T e ntelli ent el Le elin and odal o in ystem LA is a mo ile e a in e elin station desi ned and ilt to en an e end an e and an e o small s ale a tonomo s nmanned eli o te s i a e e omin in easin ly o la o a ide an e o non milita y a li a tions s as s eillan e e onnaissan e t a monito in eme en y es onse a i lt al s ayin and many ot e eye in t e s y missions T e ima y n tion o LA is to o ide a sa e le el landin lat o m o s eli o te s Additionally in o de to o ide t e maxim m ene t in te ms o in eased an e and i t time LA m st e st ate i ally lo ated in t e o eld o t e eli o te n t is a e e dis ss ot t e desi n o t e indi id al LA node and t e se o LA it in a la e systems ontext At t e node le el t e me ani al s systems im lementin t ese LA a e des i ed At t e system le el e e o t on initial es lts ta lin t e LA la ement o lem it a eneti sea al o it m n om ination t ese ont i tions o ide a om lete sol tion to ena le lon e and mo e om lex missions o small a tonomo s eli o te s**

I. INTRODUCTION

In this paper we present the design, implementation, and motivating applications of a novel Intelligent Self-Leveling and Nodal Docking Systems (ISLANDS) for small, unmanned helicopters. These small ($<$ 150kg) helicopters are used for a wide spectrum of applications including: surveillance, traffic monitoring, hot-spot detection after forest fires, port monitoring, border patrol, oil/gas pipeline inspection, search and rescue, and other missions that require an "eye in the sky" capability. Vertical take-off and landing vehicles (VTOLs) are a good fit for these applications due to their ability to hover, fly in very low altitudes, and take off and land without a runway. One drawback of small VTOLs is the limited range and flight time compared to similar sized fixed-wing aircraft. ISLANDS is designed to help alleviate this problem and increase the level of autonomy and mission complexity achievable by these systems.

ISLANDS is a standalone, self-leveling recharging/refueling station for small-scale helicopters. Currently, unmanned helicopters are usually deployed and recovered from the same location. By strategically deploying ISLANDS throughout the mission environment, unmanned helicopters can operate for longer periods of time without human involvement.

In this paper, we describe and evaluate ISLANDS from two perspectives: (1) the design and implementation of the system, and (2) the placement of multiple ISLANDS in the field of work.

A. ISLANDS Design

For ISLANDS to act as a recharging/refueling station for unmanned helicopters it must, provide a safe landing surface. As a helicopter approaches the ground, the thrust required to produce lift decreases dramatically – a phenomenon known as "ground effect" begins to affect the rotor disc. Therefore, the landing surface side dimensions must be larger than the main rotor diameter of the helicopter. Additionally, the surface must be level, which according to the Federal Aviation Administration (FAA) means level within five degrees of the environment. If the landing surface is uneven, ground effect will lead to uneven loading of the rotor disc, making a safe landing difficult. Additionally for refueling, recharging and data exchange, a latching mechanism is needed to secure the helicopter to ISLANDS.

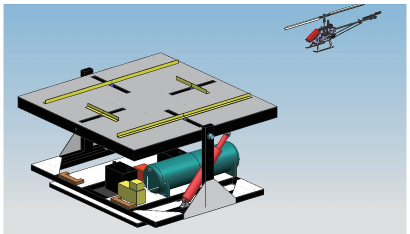

Fig. 1. CAD drawing of ISLANDS with an autonomous helicopter coming in for a landing.

The ISLANDS system presented in this paper is shown in Figure 1. To provide a level landing surface, two degrees of freedom (DOF) are required: the first is accomplished by a DC motor that rotates the platform to align with the gradient, and the second via a pneumatic piston. We have designed ISLANDS to meet this requirement for surface gradients of up to 25 degrees (we choose 25 degrees as the upper limit as this is the maximum slope that a Humvee is capable of climbing) within 20 seconds. We have also designed ISLANDS to support a helicopter of up to 150kg.

B. ISLANDS Placement

In order to utilize a group of ISLANDS effectively, they must be properly dispersed in the field. Given an area that must be monitored and a path to achieve full coverage that is longer than the flight endurance of the helicopter, what is the best way to place landing and refueling nodes in the field?

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valves operate similarly to servo motors, where they can be commanded to be either fully open, fully closed, or at any position in between, thereby varying the orifice size of the valve and, hence, the flow rate into the piston chambers. Varying orifice size of the valve is directly related to flow rate and hence change in pressure in the piston chambers these were the first valves to be used [5]. More recently on/off solenoid valves are being used due to the cost savings, were servo valves cost \$400, solenoid valves can cost as little as \$30 [7].

The signal controlling the on/off solenoid valve is that of Pulse Width Modulation (PWM). PWM is also used to control the velocity of DC motor where a carrier wave with a fixed frequency and a varying duty cycle controls the flow of electricity to a motor. In the case of a pneumatic system, when the duty cycle to the valves is set to 75% the result is that the valve is open 75% of the time, and the flow rate is reduced to 75% of maximum. Thus, by using inexpensive on/off valves, it is possible to control the pressure going into the chambers of the piston and therefore the position and velocity of the piston. One important difference between solenoid valves and transistor switches used for regulating electrical power is the switching time. Transistors switch almost instantly once a signal is applied, while solenoids have a significant delay since the coil needs to energize before the switching takes place. This delay must be accounted for in the control law development.

The control problem thus reduces to determining the appropriate duty cycle to send to the on/off valves to achieve the desired position of the piston. One of the first methods successfully used was Proportional, Integral and Differential control (PID) [18], [11], [17], [9]. These example of PID control can be considered fixed mode PID since the gains are set permanently. The problem encountered with this control method is that as the load varies, the PID gains become suboptimal for the new mode of operation. For this reason, fuzzy and neuro-fuzzy PID controllers are used [6], [17], [11], [19] that update or learn the gains needed during operation. Other controllers used include sliding mode controllers and nonlinear controllers [12], [15]. The authors in [9] compared the errors from set point of PID, fuzzy, and sliding mode controllers, with and without chamber pressure feedback using several different trajectories. The results showed that for the simplest staircase based trajectory, a PID controller with no pressure feedback performed the worst, but by only 15%. The stair case trajectory most closely resembles the operating regime of the pistons on ISLANDS and for this reason a PID controller is chosen, as it is easily implementable and produces desired results with errors within acceptable tolerances.

C. Resource Placement

The ISLANDS placement problem is similar to wireless sensor networks problems that require the location of antennas to achieve maximal coverage by demand nodes. The way the wireless sensor network community initially solved this problem is by using the work from the field of resource allocation [20]. One of the original formations for these problems was presented in [21] and is called the Maximal Covering Location Problem (MCLP). The objective function of MCLP is to maximize the demand points covered. The constraints associated with the MCLP make sure that each demand point is only covered by one supply point. Another constraint forces the number of demand points assigned to stay within pre-specified value of supply nodes.

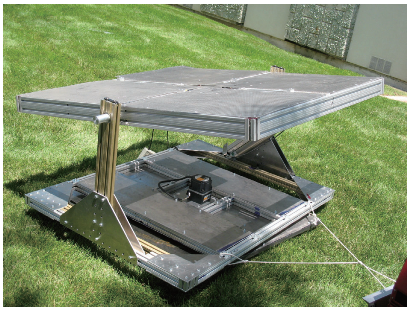

Fig. 2. Assembled Platform

The problem with MCLP is that it maximizes the area covered given q facilities and does not guarantee 100% coverage. This means that the objective function is maximized at the cost of some nodes not being covered, which violates our problem statement requiring all demand nodes are covered. A formulation that does guarantee all demand points are covered is the *p-median problem* [1]. The drawback of the p-median problem is it does not have a limit on distance between demand and facility nodes. To address this problem, we added an additional maximum distance constraint between supply and demand nodes. The addition of this constraint results in scenarios that are not solvable if there are not enough supply nodes in the scenario.

Both p-median and MCLP problems are considered NP-Hard problems [22] meaning finding the optimal solution for large problems requires testing all possible combinations and is not practical. Therefore different heuristic methods have been proposed, such as Lagrangian relaxation in which the constraints are eased [23]. Another heuristic method is genetic algorithms (GA) [19] which we used as it has been shown to successfully solve these problems with in reasonable time [1], [22].

III. SYSTEM OVERVIEW

A. Complete Mechanical System Overview

One of the design requirements of ISLANDS is that it levels with the environment. The proposed solution uses two degrees of freedom (DOF): one to rotate the platform to align with the gradient and the other to level to the gradient. An alternative design considered was a Stewart platform. However, the high mobility of a 6 DOF Stewart platform was deemed un-necessary for this application, as leveling needed by ISLANDS is achievable by 2DOF. The complete assembled system is shown in Figure 2. The leveling system is comprised of a DC motor coupled to a 3:1 gear train to rotate ISLANDS. The pneumatic piston, seen in the back

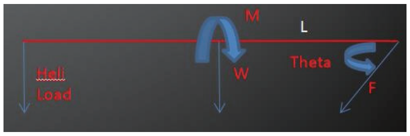

Fig. 3. Free body diagram of platform for calculating hole location

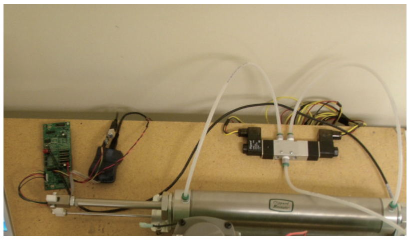

Fig. 4. Pneumatic-subsystem test bed.

corner of ISLANDS, performs the leveling to the gradient. The DC motor is placed in the center of ISLANDS in line with the Z axis. This allows for utilizing the parallel axis theorem to sum up all the inertia components of the individual components that need to be rotated to appropriately size the motor.

To determine the force required by the pneumatic piston to level the landing deck, the simplified free body diagram in Figure 3 was analyzed. Figure 3 depicts the worst case loading scenario on ISLANDS. Where the helicopter HeliLoad, is assumed to be a point load located on the far end of the landing deck and the pneumatic actuator is located on the opposite side of the load. Using equation (6) the force required by the pneumatic actuator to push the landing deck is calculated.

$$F = 2L(HeliLoad) + \frac{WL}{sin(\Theta)} \tag{6}$$

As previously stated, HeliLoad is the weight of the helicopter, W represents the weight of the top deck, M is the moment about the center of the top deck which F the force, must overcome, and L is the distance from the pivot to the attachment point of the piston. Based on this worst case scenario it was determined that the piston must be capable of producing up to 1200 N of force, with a throw range of 22 cm to achieve the +/- 25 degree required.

One of the driving factors for choosing pneumatic actuation is the high force required to level the landing deck of ISLANDS. Other actuation methods were also considered such as electric, and hydraulic actuators. Hydraulic was dismissed due to the need of hydraulic fluids and pumps. If a leak in the hydraulic system were to occur, total failure will eventually ensue due to the loss of actuating fluid. Although controlling the system is straight forward due to its inherent slow response times, and incompressibility property of the working fluid. Electric actuators where also considered but their force to power consumption is the worst of the three considered. Additionally, electric linear actuators are not back drivable, while pneumatic actuators are easily back drivable.

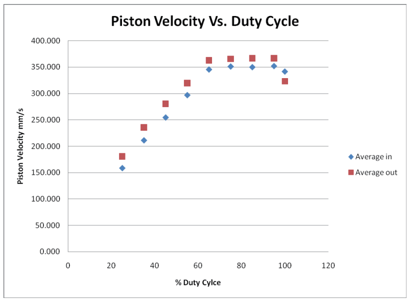

Fig. 5. Chart of Duty cycle vs. velocity

As ISLANDS uses a novel PWM-based signal for actuating on/off solenoid valves, further details of their implementation is presented. The pneumatic actuation is achieved by using a 4-way 3-position pneumatic valve actuated by two 24 VDC solenoids, a 6.3 cm diameter bore 2-way piston with a 30cm throw. A 4-way 3-position valve is used because the default sate of the valve is that both chambers are closed and hence the piston holds its position. A linear transducer with .01% linearity is used for position feedback during testing. In the future, to avoid the need for inverse kinematic calculation, an inclinometer for position feedback will be used. A microcontroller is used to generate the PWM signal based on the controller implemented. The test bed used for initial testing is depicted in Figure 4.

B. *Pneumatic System Description and Results*

The first step in the controller design is to determine the delay time associated with the solenoid valves. Experimentally, it was determined that the delay time on the valves is 8ms. This was done by generating a 20Hz carrier wave and slowly increasing the duty cycle from zero until the valve completely opened and closed. Once the minimum duty cycle was determined, an experiment was set up to determine the piston behavior under varying duty cycles. In the experiment, the valves were pulsed continually at different duty cycles ranging from 25% to 95%, while the piston went from retracted to extended position and back. From the data we were able to determine the piston velocity under different duty cycles. The results of the experiment are presented in Figure 5. An interesting observation from the experiment is that at roughly 65% duty cycle, the piston velocity peaks at 345mm/s for in and 362mm/s for out. Based on the experiments the upper and lower saturation limits of the controller are determined as being 16% and 65% duty cycles respectively.

Using the information gained from the first two preliminary experiments, a proportional controller was implemented. The controller uses position information to generate the appropriate signal to the appropriate valve. This ensures that only one valve is working at at time. To test the controller, a staircase trajectory was given to the controller with set points of 7.6, 15.2, 22.9 cm and a half second delay at each set point. Additionally, a buffer of 1mm was given to the system which is within system specification of

Fig. 6. System response to moving from 7.6cm set point to 22.9cm set point

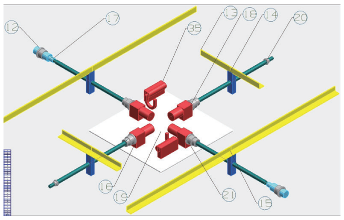

Fig. 7. CAD drawing of centering mechanism with latching actuators

level. Different combinations of proportional and differential gains were tested with the staircase trajectory. After the experiments, it was determined that due to the slow response of the system a differential gain is un-necessary. Figure 6 shows the results from five proportional gains tested 10, 20, 30, 40 and 50 to going from a set point of 7.6cm to 15.2cm. As can be seen, the higher the gain the faster the response was but at a gain of 50 there is some overshoot, hence a gain of 40 was selected. Using a proportional controller the piston is able to cover 7.6cm in 0.45 seconds which is within the time requirements of the system.

C. Centering Mechanism

The top landing deck of ISLANDS houses the electronics and actuators necessary for centering and latching of the helicopter for refueling/recharging and data exchange. The centering mechanism system is designed to take into account the errors associated with both the vision and attitude controller on board an autonomous helicopters. By having the helicopter land roughly in the right spot on ISLANDS, the centering mechanism then moves the helicopter to a pre-defined center position. The centering mechanism is composed of four motors attached to Acme rods which pull a blade across the surface of the platform. The motors currently being used are 12VDC motors rotating at 263RPM with a stall torque of 2527oz-in or 181 kg-cm. The motors were chosen for their size and cost and are capable of moving 50kg helicopter, with aggressive friction coefficients of .25 taken into account. The acme thread used is a 2 thread per/cm rod, which means the centering procedure takes a total of 1 minute with the motors rotating at full speed. Figure 7 is a CAD model showing the inner workings with the latching mechanism still to be implemented.

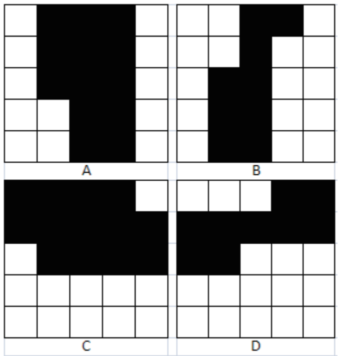

Fig. 8. Different possible Zamboni path between two points

Fig. 9. Results to GA implementation

IV. AREA COVERAGE RESULTS

The GA implemented is based on [1] as stated previously. The area is modeled as a discretized square area made up of n x n elements. Each element represents the field of vision of the sensor placed on the helicopter. Each of the discretized elements represents a ”demand” location that the helicopter must survey. The Manhattan distance between adjoining cells is assumed to be uniform making distance calculation simple. This configuration allows the solution to scale to real world applications. As each grid center location can be associated with a GPS via point, which a helicopter will then use to implement via point navigation.

Two distance matrices are used for calculating the fitness of the chromosomes in the GA. One is based on Manhattan distances, where the distance from start to finish is defined as:

$$d_{\mathsf{sf}} = |x_{\mathsf{s}} - x_{\mathsf{f}}| + |y_{\mathsf{s}} - y_{\mathsf{f}}|. \tag{7}$$

The other distance matrix is based on “Zamboni” distances. Zamboni distances are based on cells covered between start and finish as seen by sub-figure a-d in Figure 8 which takes into account all the different possible patterns that can be taken between two points given 4 point connectivity. Distance calculations are performed offline and then loaded into the GA. Similarly, an offline algorithm is used to create the initial population based on how many ISLANDS nodes are to be placed.

All tests were performed on a 10x10 grid creating 100 demand points. The first test used Manhattan distances with one ISLANDS supply station; this produced the expected answer of ISLANSD being placed in the center of the grid. The next test performed uses 5 ISLANDS supply stations and no distance constraint. The results of this experiment is shown in Figure 9(a) and a star pattern of ISLANDS nodes is produced, which makes sense intuitively. The next problem solved, had a distance constraint of 5 between an ISLANDS node and any demand node, while still using the Manhattan distance metric. The program was run incrementally starting with 1 ISLANDS node until a feasible solution was found. This yielded the need for a minimum of 4 ISLANDS nodes for this scenario and the placements are shown in Figure 9(b).

The next two experiments conducted were those imposing a distance constraint of 10 and 5 nodes between an ISLANDS node and demand nodes. With the major difference being that the Zamboni distance metric was used. For a distance constraint of 10 nodes, 4 ISLANDS nodes were needed and are dispersed around the perimeter as shown in Figure 9(c). For a distance constraint of 5 nodes 12 ISLANDS were needed and are dispersed as seen by Figure 9(d). This increase in ISLANDS nodes from the previous experiment using Manhattan distance metric is because using a Zamboni pattern limits the distance that can be covered but increases the coverage. As can be seen in the simple example of Figure 10 the Zamboni distances range from 9 to 13 units while the Manhattan distance is 5 units.

V. CONCLUSION

In this paper we present the ISLANDS system which is being designed to increase the endurance of unmanned helicopters in the field. We propose a system that is capable of providing a safe landing area, which incorporates both leveling to the environment and a latching and centering mechanism for the helicopter. The leveling system is composed of a 2DOF mechanism one of the degrees of freedom being pneumatic. This pneumatic piston is actuated via a PWM signal controlled by a proportional controller. The centering mechanism developed is used to bring the helicopter into reference frame with ISLANDS which will allow for future work on refueling recharging and data exchange.

Lastly, we presented part of the solution for optimally placing ISLANDS nodes to help in maximizing the missions of the unmanned helicopters. The GA used takes into account the Zamboni-based search pattern employed by the helicopter and the endurance of the helicopters. We present initial results of this GA that are promising, and will serve as a stepping stone for the development of more optimal flight paths that take advantage of the locations chosen for ISLANDS.

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