

Towards Micro Aerial Manipulation Using a Computational Compensation Strategy

Aaron Eleazar Lopez Luna ^{*1}, Jose Martinez-Carranza^{1,2}, and Israel Cruz-Vega¹

¹Instituto Nacional de Astrofísica, Óptica y Electrónica, Mexico

²University of Bristol, UK

ABSTRACT

This paper presents an aerial manipulation system for low-cost micro air vehicles, which consist of two degrees of freedom robotic arm attached to the lower part of the vehicle, this vehicle is a commercial aerial vehicle parrot bebop-2. Thus, we propose to extend the capabilities of this inexpensive vehicle towards aerial manipulation. For the latter, this work presents a novel structure design which allows the bebop-2 to carry a manipulator in the lower part of the structure. The conventional proportional-integral-differential (PID) control algorithm used in most of these kind systems is not sufficient to deal with the new stability problems involved in this novel system. Therefore, to improve the control effectiveness, a computational-based compensation strategy based on the k-nearest neighbors (KNN) algorithm is incorporated into the control loop. KNN strategy can provide the adequate compensation at a low computation cost and is promising for real-world application. Experimental results developed in this work demonstrate a satisfactory performance for the proposed robotic arm design and the proposed control technique.

1 INTRODUCTION

Mobile manipulators (robotic manipulator arms attached to mobile bases) research has grown in recent years due to the importance and popularity of this useful systems in industrial and commercial applications. Ground mobile manipulators have been researched for use in areas like marine, agriculture, space and industrial applications [1, 2, 3]. Although many works and research mainly focus on the use of mobile ground systems, aerial vehicles have become widespread and more pervasive in research and technological development. Aerial vehicles are attractive due to their navigation capability in large areas where humans can not access or where mobile ground systems [4] may not perform adequately. In addition to the plethora of applications that can be developed with

aerial systems (e.g., precision agriculture, video photography, infrastructure inspection, etc.), there is a growing interest for combining these aerial platforms with robotic manipulators, by attaching them to the aerial structure in order to obtain a new configuration of aerial manipulation systems [5]. Aerial systems like Unmanned Aerial Vehicles (UAVs) or drones, can be either controlled from the ground station, or by autonomous on board control algorithms. The interest in using this type of system comes not only from its dynamics, which represent an attractive control problem but also from the design issue. Notably, the researchers focus on the optimization of operational algorithms [6, 7, 8].

According to literature, the quadcopter is one of the most efficient configurations to implement an aerial manipulator due to their superior mobility in comparison with other available configurations [1, 2, 8, 6, 7]. Aerial manipulators open a new application area for robotics and aerial systems. Nevertheless, this new configuration represents a new problem in the stability control of the aerial vehicle. Movements of a manipulator attached to a VTOL during flight mode bring about disturbances which can cause instability and the loss of the entire system. New models and control algorithms have been proposed to prevent this situation [4, 9]. The leading proposals to ensure an admissible flight performance are; restricting the movement of the manipulator, incrementing the torque of actuators of the system, consider the change of mass distribution in the model and consider the influence of the motion of manipulator in system dynamics [10].

In this work, we consider the proposal of taking into account the changing of the behavior of the UAV due to the movement of the arm and we propose an experimental study to determine the variation in plant dynamics and an appropriate correction in the attitude control to approximate the real trajectory of the system to the desired trajectory. Therefore in this work we propose a novel design of an aerial manipulator arm with two degrees of freedom (DOF) attached to a commercial quadcopter parrot bebop-2. We also propose to incorporate a computational compensation strategy to a Classical PID control to ensure the stability of the proposed aerial manipulator. We determine the values for the computational compensation by the experimental study; this represents a novel technique to deal with the drawbacks of perturbations in the aerial manipulation systems.

*Email address: aaron.eleazar@inaoep.mx

The computational compensation strategy is based on the k-nearest neighbors (KNN) algorithm.

KNN method has attracted the attention of the research community due to its simplicity and effectiveness [11]. This technique has a wide range of applications such as density estimation, dimensional hashing, pattern recognition, data compression, and so on [12]. The nearest neighbor search is an optimization problem, whose goal is to find an instance that minimizes a certain distance or similarity function [11, 12]. In this work, we utilize the KNN algorithm to classify the noise induced by the movement of the arm of the manipulator in order to infer and send a compensation signal to the stability control of the aerial system. The main reason for the election of the KNN method is the requirement of a not a complicated training process to set up a classifier and only utilizes the labeled training set to classify the testing data.

This paper is organized as follow: In section 2 the novel proposed aerial manipulation system is described. The PID control technique and the compensation strategy developed for this work are presented in section 3. In section 4 the PID control with compensation is described. Three type of experiments were implemented to prove the effectiveness of the proposed strategy. Such experiments, and the obtained results are described in section 5. Finally, the main contribution, conclusions, and future direction are discussed in section 7.

2 DESCRIPTION OF PROPOSED SYSTEM

Among the different configurations of UAV systems, the VTOL vehicle has been taken into account specially for aerial manipulation due to their specific aspects in the flight mode. Particularly, the quadcopter is used in this work to achieve the primary goal of maintaining the robot manipulator in the desired point. In this work, an aerial manipulator is designed. The system consists of two primary subsystems: the aerial vehicle of four rotors and a robotic arm of two DOF. In the following subsections, each one of this system is presented.

2.1 FOUR ROTOR STRUCTURE

Due to the four rotors, the quadcopter has more lifting power than a helicopter of the same size, allowing to carry on a heavier payload. In Figure 1 a four-rotor structure model is shown, which corresponds to the physical structure of a parrot bebop-2. Also in this figure illustrated our own design of the two DOF arm attached to the bebop-2. The robotic arm was designed specifically for this aerial vehicle taking care of the dimensions and weights of each piece in order to assure most possibly the stability of the vehicle during the flight. Four extension legs were also designed to provide free taking off and landing of the aerial vehicle when carrying the arm.

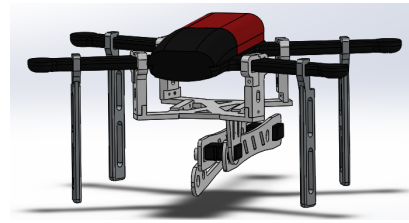


Figure 1: CAD of 2 DOF robotic arm.

2.2 ROBOTIC ARM

In the task of manipulation and interaction, robotic arms can provide the necessary degrees of freedom to achieve the objective [13, 2, 8]. In contact with the environment, for example, an n-DOF arm could supply the stiffness and versatility to the vehicle to accomplish the goal involving contact with a rigid structure. The N-DOF arm could also designed to provide a safe distance between the aerial system and the structure.

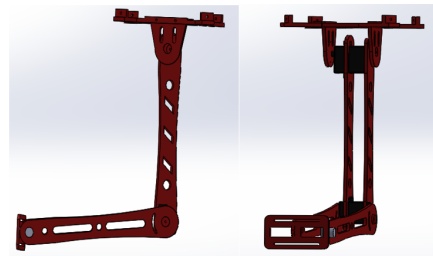


Figure 2: CAD of 2 DOF robotic arm.

Figure 2 shows our design of the two DOF-arm for the bebop-2 structure. The design was developed thinking in two main aspects. First, the physical task. The task consists in exert a force on a rigid surface. For this objective, the robotic arm must provide the necessities movements to successfully contact the surface and also must provide adequate distance from the vehicle to the surface to reduce the disturbances induced by the proximity of the rigid structure with the rotors of the aerial vehicle. Secondly, the dimensions of the proposed design must maintain a relationship with the physical capabilities of the system guarantying the typical performance in the flight mode. Even with this consideration, the behavior of the robotic arm can alter the efficiency of the vehicle, for this reason, a control technique which considers the perturbations of the robotic arm must be implemented to achieve the proposed task. In the following sections, the problem of perturbations and the proposed solution is handled.

3 BACKGROUND

This section presents the background theory of the PID control and the KNN strategy, as a computational-based compensation strategy incorporated into the control loop.

3.1 PID CONTROL DESIGN

Considering that the dynamical model of the quadcopter is an under actuated, highly coupled and nonlinear system, a considerable number of control strategies have been developed for such class of similar systems [14, 15]. Among them, sliding mode control, which has drawn researchers' much attention, has been an useful and efficient control algorithm for handling systems with significant uncertainties, time-varying properties, nonlinearities, and bounded external disturbances. Most of the control strategies mentioned above have been proposed to help in the stability of the quadcopter on finite-time. A PID controller continuously calculates an error value $e(t)$ as the difference between the desired set point and a measured process variable and applies a correction based on proportional, integral, and derivative terms, (sometimes denoted P, I, and D respectively). The PID algorithm is described by:

$$u(t) = k_p e(t) + k_I \int e(\tau) d\tau + k_D \frac{d}{dt} e(t) \quad (1)$$

In equation 1 k_p , k_I , k_D are the PID control gains, $u(t)$ is the control signal and $e(t)$ is the control error. The integral, proportional and derivative part can be interpreted as control actions based on the past, the present and the future. The PID gains can be designed based upon the system parameters if they can be achieved or estimated precisely. We mentioned next some related works. In 2010 Pual E. I. Pounds et al. [16] developed a dynamic model of an aerial manipulation system during object capture by combining a simple planar model of a helicopter UAV in hover under PID control with a suspended bogie linkage representation of a compliant gripper. Matko Orsarg et al. [17] proposed a proportional controller for the speed loop and a proportional integral controller for the position loop taking into account the dynamics of the system composed by a VTOL vehicle with a 2 DOF manipulator. A PID controller is designed for the x and y position and yaw orientation of the aerial vehicle.

3.2 K NEAREST NEIGHBOR COMPUTATIONAL COMPENSATION STRATEGY

KNN is a non-parametric method used for classification problems. The method requires the construction of a data base consisting of training examples, where each example $f(x)$ is represented by a set of n attributes $f = (a_1, a_2, \dots, a_n)$ and a corresponding class x . Once the data base is ready, the classification model consists of an input vector for which the class is unknown. The output is a class membership inferred by a majority vote of the k nearest examples found in the data base.

In sum, the KNN algorithm consists of two main phases: training and classification. The training phase comprises only of storing the feature vector examples and class labels of the training samples $\langle x, f(x) \rangle$, where $x \in X$, where X is the set of all classes.

In the classification phase, an unlabeled vector (f) is classified by assigning the label which is most frequent among the k training samples nearest to that query point; the following equation describes this phase of the KNN algorithm:

Therefore, in this work, our goal is to use the KNN algorithm as the means to generate a model that has knowledge on what control signal should be used to compensate for a disturbance. The next section will describe this proposed approach.

4 PID CONTROL ALGORITHM WITH COMPENSATION STRATEGY

We performed several runs where we associated a control signal u_c with the vehicle's motion disturbance f derived from the arm's motion. These disturbances were observed via the motion capture system in the manner of shifts of the vehicle's position P concerning to the set point in the air. In this manner, we created a database (see Table 1) containing the arm's disturbance coupled with the vehicle's shifts. We consider this a learning stage in our compensation approach.

f		P	U_c
$f(p_1)$	1	p_1	U_{c1}
	.	.	
	.	.	
$f(p_i)$	i	p_i	U_{ci}
	.	.	
	.	.	
$f(p_N)$	N	p_N	U_{cN}

Table 1: Database structure.

Once the database was created, a compensation scheme is implemented by inferring the nearest disturbance effect f in the vehicle's motion given an arm's disturbance. According to variation of real trajectory of the system a correction U_c necessary to get back the system to the desired trajectory is determined. Equation 2 represents the new control signal.

$$u(t) = k_p e(t) + k_I \int e(\tau) d\tau + k_D \frac{d}{dt} e(t) + u_c \quad (2)$$

This is, in a new flight test, we generate a disturbance with the arm's movement, and at the same time, we seek out the most similar disturbance recorded in our database in order to obtain a value representing the expected vehicle's shift position, this value will be used to compensate the signal in the PID controller of the vehicle's flight. For the implementation of the algorithm, we choose $N=10$. In sum, we employ a 1-Nearest Neighbor approach, also known as lazy learning in computational terms, to infer a disturbance given a set of examples previously experienced. Our hypothesis is that, by inferring this disturbance, the PID controller will struggle less to maintain the vehicle's motion around the set point. In the

following section, the development of the control technique is detailed.

5 EXPERIMENTAL SETUP

The proposed control strategy was proved via experimental tests in a controlled environment. We considered physical dimensions of bebop-2 to determine the appropriate design of the manipulator. The two degree of freedom (DOF) robotic arm is composed of 2 links with a dimension of 10 cm (L), 0.3 cm (W) and 4 cm (H), each one with 0.12 kg (m). An Arduino Nano board was used to control the manipulator.



Figure 3: Aerial Manipulation system implemented for this work.

The proposed system is shown in Figure (3), the CAD model shown in section 2.1 (a) was developed first to estimate the proper dimension of pieces, then the manipulator was built using 3D-print technology. Finally, all components were attached to the bebop-2 vehicle (b). The Figure 4 shows the block diagram for this research. In this representation $E(t)$ represents the error between the desired position and the real position, $Y(t)$ represents the control commands sent to the aerial vehicle to control the attitude. A PID control was implemented to each signal of the position of the system (x , y , z , yaw). The VICON cameras were used to get the position of the system continually.

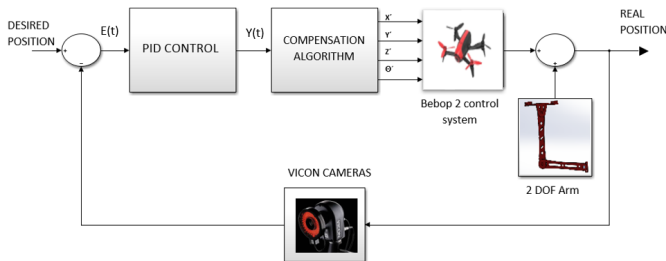


Figure 4: . Block diagram of the proposed system with compensation strategy.

The instability due to the arm is represented as noise in the block diagram that affects the position of the vehicle directly. The objective is to compensate this displacement in

order to maintain the aerial vehicle in the desired position. The disturbance of the robotic arm is compensated by the PID control with a compensation signal.

To prove the necessity of a compensation control for the stability of the bebop-2, a case of study of the behavior of the system in hovering mode was done. Figure 5 show the shifted position of bebop-2 from desired point (0,0,1) due to the arm. The result illustrates the necessity to implement a control algorithm to help the inner control of the bebop-2 to maintain stability. Three experiments were implemented to prove the proposed control technique. Figure 6 shows the proposed movements of the robotic arm to implement the compensation strategy. The manipulator arm start in the initial position (1 and moves until the final position 4). In the following section, the results of these experiments are detailed.

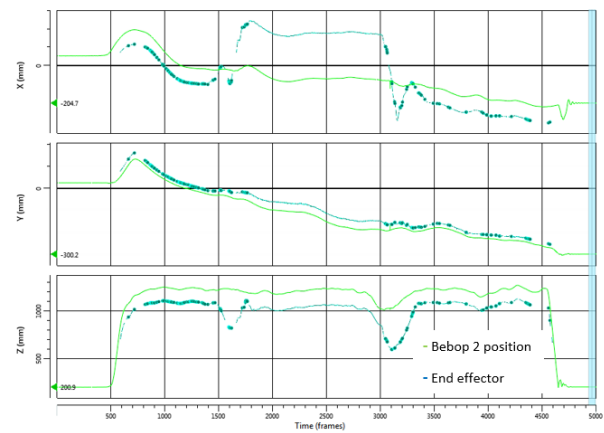


Figure 5: Hovering mode results. Behavior of the aerial vehicle carrying the robotic with movement.

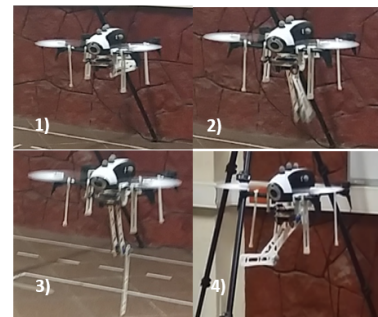


Figure 6: First sequences of Movements of the robotic arm during flight mode.

6 RESULTS

In the first experiment, the PID control 3.1 is implemented to maintain the aerial manipulator at the desired point; the arm does not move during this experiment. The graphics of

Figure 7 shows the position of the system in x-axis and y-axis, yaw orientation is also included. The PID control is trying to maintain the vehicle in position (4, 3, 1). The x-axis of the three graphics represents the position in millimeters (*mm*) and the y-axis of the graph represents the time in milliseconds (*ms*). In this example, the PID control maintains the system among (0.2, -0.2) in all axes.

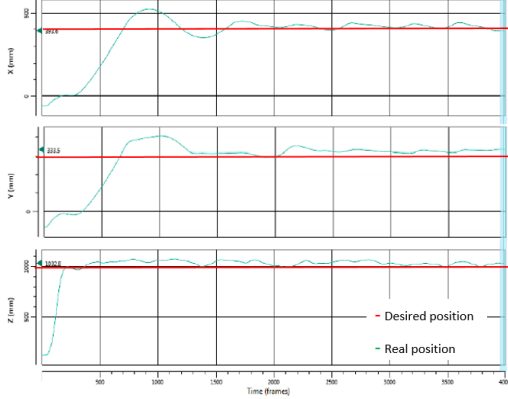


Figure 7: PID control results. Behavior of the aerial vehicle carrying the robotic arm but the arm is not moving.

In the second experiment, the arm executes predefined movements as described in Figure 6, in this experiment the PID control is incapable of ensuring the stability of the system at the desired point. The error $e(t)$ is above 8 cm. Bebob 2 is located in position (0, 0, 1) when the robotic arm starts to move. Two blue fringes highlight the lapse time where the arm is moving, left fringe indicates the movement of the arm from initial position (1 to final position (4 and right fringe indicate the movement of the arm to return to initial position. Figure 8 shows that the displacement of the system continues even when the arm stops moving.

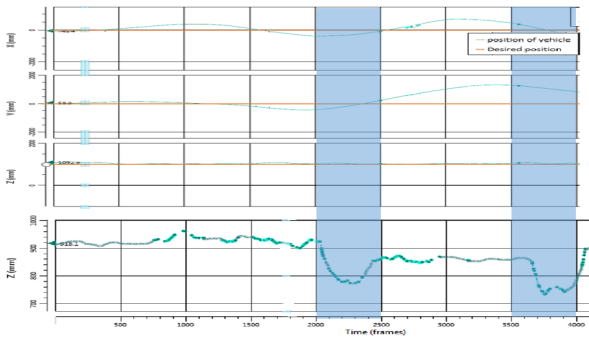


Figure 8: PID control results. Behavior of the aerial vehicle carrying the robotic arm and the arm is moving.

To improve the effectiveness of the PID control, the compensation strategy described in section 3.2 is implemented. Now the PID control is able to compensate for the disturbance

produced by the arm. The graphics of Figure 9 shows the position of the system in the x-axis, y-axis, and yaw orientation. When comparing graphics of Figure 8 and Figure 9, the effectiveness of the PID control with compensation strategy is demonstrated.

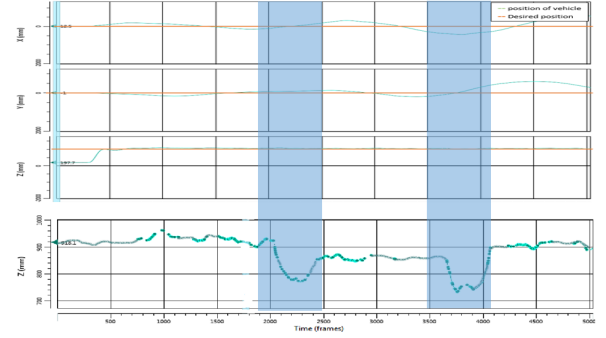


Figure 9: PID control with compensation results. Behavior of the aerial vehicle carrying the robotic arm and the arm is moving

For the purpose of quantitatively compare the control performance we defined the following function:

$$mse = \frac{1}{n} \sum_{i=1}^n (e_i)^2 \quad (3)$$

Equation 3 describe the mean squared error (mse) where $e_i = p_d - p_r$ represents the error value between desired position p_d and real position p_r of the system in the time i . The quantitative results for each controller are given as in Table 2. According to the experimental results, the disturbance induced by the arm seems to affect position x more than in the others positions, this is owing to the arm moves in the x plane and the displacement in the other positions is the result of the adjustment of the control in the rotors of the vehicle. Comparing results we observe that an upgrade in the performance and response has achieved with PID control with compensation.

mse	Hovering	PID control	PID + comp.
X	42.56	14.12	5.25
Y	26.44	11.45	2.98
Z	7.65	4.95	1.62
θ	4.2	2.6	1.02

Table 2: Mean squared error.

7 CONCLUSIONS

We have presented a novel aerial manipulation system. Our novel design is affordable and can be produced via 3D printing technology. Experimental studies were made with the aerial manipulator developed in this work to determine physically the variation of dynamics and deterioration of the

<https://www.imavs.org/pdf/imav.2018.11>

performance of the air vehicle due to the incorporated arm. We have also presented preliminary results regarding a control strategy to maintain stable flight of the vehicle while the arm performs a task. The strategy involves the use of a computational approach based on soft learning, where a training stage is carried out in order to create a database confirmed by examples of disturbances induced on the vehicle and derived from the arm's motion, and we related them to the control signals sent to the arm. Thus, in the test stage, when we sent a control signal to the arm, we infer from the learned database the vector disturbance that may arise. After that, we use such information to compensate for the disturbance by adding a correction signal to the PID controller calculated in the experimental study phase. This represents a novel technique to deal with the drawbacks of perturbations in the aerial manipulation systems. The main contribution of this work is the novel control technique based on a traditional PID algorithm with a compensation strategy and the two- DOF arm to the aerial vehicle.

Link of video: <https://youtu.be/2BB0aDr6-IQ>

REFERENCES

- [1] C. D. Bellicoso, L. R. Buonocore, V. Lippiello, and B. Siciliano. Design, modeling and control of a 5-dof light-weight robot arm for aerial manipulation. In *Control and Automation (MED), 2015 23th Mediterranean Conference on*, pages 853–858, June 2015.
- [2] S. Bouabdallah and R. Siegwart. Full control of a quadrotor. In *2007 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 153–158, Oct 2007.
- [3] D. Bazylev, A. Kremlev, A. Margun, and K. Zimenko. Design of control system for a four-rotor uav equipped with robotic arm. In *Ultra Modern Telecommunications and Control Systems and Workshops (ICUMT), 2015 7th International Congress on*, pages 144–149, Oct 2015.
- [4] T. Bartelds, A. Capra, S. Hamaza, S. Stramigioli, and M. Fumagalli. Compliant aerial manipulators: Toward a new generation of aerial robotic workers. *IEEE Robotics and Automation Letters*, 1(1):477–483, Jan 2016.
- [5] P. E. I. Pounds, D. R. Bersak, and A. M. Dollar. Grasping from the air: Hovering capture and load stability. In *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, pages 2491–2498, May 2011.
- [6] M. Bernard and K. Kondak. Generic slung load transportation system using small size helicopters. In *Robotics and Automation, 2009. ICRA '09. IEEE International Conference on*, pages 3258–3264, May 2009.
- [7] K. Baizid, G. Giglio, F. Pierri, M. A. Trujillo, G. Antonelli, F. Caccavale, A. Viguria, S. Chiaverini, and A. Ollero. Behavioral control of unmanned aerial vehicle manipulator systems. *Autonomous Robots*, 41(5):1203–1220, Jun 2017.
- [8] L. R. Buonocore, J. Cacace, and V. Lippiello. Hybrid visual servoing for aerial grasping with hierarchical task-priority control. In *Control and Automation (MED), 2015 23th Mediterranean Conference on*, pages 617–623, June 2015.
- [9] Fabio Ruggiero, Jonathan Cacace, Hamid Sadeghian, and Vincenzo Lippiello. Passivity-based control of {VToL} {UAVs} with a momentum-based estimator of external wrench and unmodeled dynamics. *Robotics and Autonomous Systems*, 72:139 – 151, 2015.
- [10] F. Santoso, M. A. Garratt, and S. G. Anavatti. State-of-the-art intelligent flight control systems in unmanned aerial vehicles. *IEEE Transactions on Automation Science and Engineering*, 15(2):613–627, April 2018.
- [11] J. Zhang, M. Gao, W. Chen, and G. Shen. Non-data-aided k-nearest neighbors technique for optical fiber nonlinearity mitigation. *Journal of Lightwave Technology*, 36(17):3564–3572, Sept 2018.
- [12] Jorge Gonzalez-Lopez, Sebastin Ventura, and Alberto Cano. Distributed nearest neighbor classification for large-scale multi-label data on spark. *Future Generation Computer Systems*, 87:66 – 82, 2018.
- [13] S. Kannan, M. Alma, M. A. Olivares-Mendez, and H. Voos. Adaptive control of aerial manipulation vehicle. In *Control System, Computing and Engineering (ICCSCE), 2014 IEEE International Conference on*, pages 273–278, Nov 2014.
- [14] C. E. Doyle, J. J. Bird, T. A. Isom, C. J. Johnson, J. C. Kallman, J. A. Simpson, R. J. King, J. J. Abbott, and M. A. Minor. Avian-inspired passive perching mechanism for robotic rotorcraft. In *2011 IEEE/RSJ International Conference on Intelligent Robots and Systems*, pages 4975–4980, Sept 2011.
- [15] S. Tang and V. Kumar. Mixed integer quadratic program trajectory generation for a quadrotor with a cable-suspended payload. In *2015 IEEE International Conference on Robotics and Automation (ICRA)*, pages 2216–2222, May 2015.
- [16] Aaron Dollar Paul E. I. Pounds. Hovering sability of helicopters with elastics constraints. *ASME Dynamic Systems and Control Conference*, 2010.
- [17] Matko Orsag, Christopher Korpela, and Paul Oh. Modeling and control of mm-uav: Mobile manipulating unmanned aerial vehicle. *Journal of Intelligent & Robotic Systems*, 69(1):227–240, 2013.