# Scientific Report 2015

## Handling non-smooth effects in control of real robotic systems

Young Teams Project
PNII-RU-TE-2014-4-0942, contract nr.88/2015
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November 25, 2015

## Objectives of the 2015 phase

The phase objective delineated in the implementation plan was the development of models for aerial vehicles and robotic arms. Assistive robotics [1], or, specifically, the use of robotic arms is motivated by the societal need of increasing the independence of elderly and disabled people. Higher living standard may be obtained by employing robotic assistance. Aerial vehicles, in particular vertical take-off and landing ones such as quadrotors [2, 3, 4], have received a growing interest of the robotics research community due to the numerous applications that can be addressed with such systems, like surveillance, inspection, or mapping [5, 6]. However, for model-based control, these systems require methods and algorithms that are able to 1) reliably estimate variables of interest while compensating for sensor limitations and disturbances; and 2) achieve the desired control objective in spite of actuator limitations and significant changes in the model due to external, possibly discontinuous destabilizing effects. Since our objective is model-based control, in this short phase, we have focused on developing models for quadrotors such as AR Drones and robot arms, specifically a Cyton Gamma robot arm. These will be used in the next phase for testing and validating controller and observer design methods. Preliminary steps were made towards the analysis of these models and the development of local methods for estimation and control.

## 1 Model development

### 1.1 Aerial vehicles

The first class of systems that has been modelled is quadrotors. Classic models exist for fixed wing planes and helicopters. However, since commonly flying vehicles are modelled as rigid bodies, multirotors can use the same modelling principles as for instance the ones used for helicopters. The differences between various architectures are reflected in the way the flight is achieved.

Flight dynamics can be modelled using one of the following two approaches: using the equation of energy conservation and the Euler-Lagrange formalism [7, 8, 9, 10], or describing the movement (rotation and translation) of a rigid body in an inertial space, based on the Newton-Euler approach [11, 12, 13, 14, 15, 16]. The former procedure determines the translational dynamics in a simple way, but in the existing models the rotational dynamics seems to remain at a higher level of description. On the other hand, the Newton-Euler approach provides a complete relationship between rotor speed inputs and the translational and rotational dynamics of the vehicle.

Besides modelling as a rigid body, several other representation alternatives have been considered. A simpler approach is to look at the vehicle as a point mass, in situations when only the evolution of the position is relevant (e.g. in certain high-level path planning tasks). More complex models consider the vehicles as multi-rigid-bodies, or non-rigid-bodies (e.g. flapping-wing architectures). However, in case of multirotors, single-rigid-body models are sufficient. Additional dynamics specific to multirotors and helicopters, such as propeller blade flapping and induced drag [13, 17, 18] are not considered at this moment.

Quadrotors are commonly modelled using one of the two configurations presented in Figure 1.1: "plus" configuration, when the quadrotor arms are aligned with the $x$ and $y$ axes; and "cross" configuration, when the quadrotor is rotated with $45^o$ around the $z$ axis compared to the previous configuration. Since an ahead-looking camera is mounted on the cross, the latter one is preferred. In this way the forward direction corresponds to the view direction of the camera. Motor numberings and corresponding angular velocities, marked with $\omega_i$, are presented in Figure 1.1.

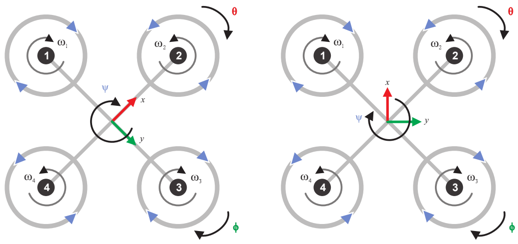

Figure 1: Quadrotor configurations: plus (left) and cross (right) configuration

We used both modelling approaches to build models for the AR Drone on which validation and testing will be performed. For the Newton-Euler approach, we built upon the procedure from [15], whereas for the Euler-Lagrange formalism, we followed the steps presented in [19, 9]. It should be noted that we did not assume a near-hovering behaviour that is commonly considered. The quadrotor is modelled as a single rigid body, having a symmetrical structure, with the origin of the body frame in the center of gravity. Additionally, the propellers are assumed to be rigid objects.

Furthermore, we have identified the parameters of the AR.Drone 2.0 quadrotor [20]. Most parameters depend on the actual quadrotor that is used, e.g., the weight of the vehicle depends on the equipment used onboard. We have performed measurements for two AR Drone 2.0 quadrotors and obtained the results shown in Table 1.

Table 1: Parrot AR.Drone 2.0 parts weight measurements

| **first quadrotor** | **mass (kg)** |
|---|---|
| fuselage | 0.293 |
| 1500 mAh battery | 0.120 |
| indoor hull | 0.057 |
| outdoor hull | 0.029 |
| GPS module | 0.033 |

| **second quadrotor** | **mass (kg)** |
|---|---|
| fuselage | 0.294 |
| 1000 mAh battery | 0.101 |
| indoor hull | 0.076 |
| outdoor hull | 0.030 |

The different weights influence the other parameters as well, specifically the moments of inertia. Therefore, although the mass will be exactly known, we might consider an uncertain model for which a robust controller will have to be designed.

In the current configuration of the system the inputs are the desired velocities. In order to obtain a better control performance, the forces and torques acting on the rotors will be used as inputs. Based on the official product specifications [21], the minimum and maximum values of these inputs have been determined.

## 1.2 Robotic arms

The second class of systems considered is robotic arms. The mathematical models that characterize a robotic arm are structured into three categories:

1. The geometrical model - representing the position and the orientation of the joints and the gripper relative to a fixed coordinate system.

2. The kinematic model - representing the velocity and acceleration of the joints and the gripper relative to a fixed coordinate system.

3. The dynamic model - representing the effect on the position and orientation of the forces and the torques acting in the physical system.

For open-chain mechanical structures, such as the robot arm, the direct models are analytical and are represented by the equations which describe the position, orientation, velocity, acceleration and active forces, with respect to a fixed coordinate system and knowing all the motion parameters of the active joints relative to their coordinate system.

The design of the control algorithms for a robot with n degrees of freedom imposes that the mechanical structure to be geometrically modeled. The geometrical model of the robot can be obtained using different methods like: vectorial method, rotation matrices, general parameters, Denavit-Hartenberg method, etc. The Denavit-Hartenberg parameters define the relative position both for the kinematic axes of the element and for the neighbor elements connected on the same motion axis, and they define the homogenous transformation between two consecutive axes.

Figure 2: Cyton Gamma 1500 robot arm

From the mechanical point of view the Robai Cyton Gamma 1500 robot arm is an open chain kinematic structure, having seven active rotation joints. The equations which define the position and the orientation of the robot gripper relative to the fixed coordinate system placed in the robot base were determined using the Denavit-Hartenberg method.

The direct kinematic model of the robot Robai Cyton Gamma 1500 implied the determination of the joints' motion vectors, angular and linear velocities, angular and linear accelerations.

Keeping in mind the objective of designing controllers, rigid bodies have been assumed. Thus, the robot elements are rigid and connected with class V joints (one degree of freedom) and are considered perfect from the friction and elasticity point of view. The dynamic model of the robot has been determined using the iterative Newton-Euler method, based on the following known parameters:

1. the mass of the elements (joint and connection element)

2. the mass center point relative the joint coordinate system

3. the moment of inertia of an element relative to the frame placed in mass center point

Each element is acted upon by external forces and torques. Therefore, in order to determine the dynamic equations of the mechanical structure, the following parameters have been determined for each element:

1. the external force acting on the mass center point of the element;
2. the external torque generated by the force;
3. the connection force between two consecutive elements applied in the origin of the coordinate system of the second element;
4. the torque generated by the connection force for each element of the system.

In the connection links of the joints have been considered geometrically simple elements, with the mass center point being placed at a half of the element length. With these assumptions an extremely complex mathematical model has been obtained. The next step consists in determining the limits of all the variables and parameters involved, together with possible ways to simplify this model.

## 2 Preliminary and other work

In a collaboration with V. Estrada-Manzo and Thierry-Marie Guerra at the University of Valenciennes, conditions for observer design for mechanical systems in descriptor form are being researched. A journal submission has been prepared.

In the context of the cooperation with J. Laubers, steps have been made towards a framework for local analysis and controller design of nonlinear systems. Several conference submissions are planned.

PI Zs. Lendek and K. Máthé have begun working on controller design for quadrotors.

Finally, Zs. Lendek will give a presentation at the 54th IEEE Conference on Decision and Control, Osaka, Japan, on the subject of unknown input estimation for nonlinear descriptor systems via LMIs and Takagi-Sugeno models. In this talk she will also outline some of the points that have been undertaken in the project.

## References


[1] Z. Z. Bien and D. Stefanov, Eds., *Advances in Rehabilitation Robotics*, ser. Lecture Notes in Control and Information Sciences. Springer, 2004, vol. 306.

[2] K. Alexis, G. Nikolakopoulos, and A. Tzes, "Switching model predictive attitude control for a quadrotor helicopter subject to atmospheric disturbances," *Control Engineering Practice*, vol. 19, pp. 1195–1207, 2011.

[3] M.-D. Hua, T. Hamel, P. Morin, and C. Samson, "Introduction to feedback control of underactuated VTOL vehicles," *IEEE Control Systems Magazine*, vol. 33, no. 1, pp. 61–75, 2013.

[4] D. Cabecinhas, R. Cunha, and C. Silvestre, "A nonlinear quadrotor trajectory tracking controller with disturbance rejection," *Control Engineering Practice*, vol. 26, pp. 1–10, 2014.

[5] D. Hausamann, W. Zirnig, G. Schreier, and P. Strobl, "Monitoring of gas pipelines – a civil UAV application," *Aircraft Engineering and Aerospace Technology*, vol. 77, no. 5, pp. 352–360, 2005.

[6] K. Chee and Z. Zhong, "Control, navigation and collision avoidance for an unmanned aerial vehicle," *Sensors and Actuators A*, vol. 19, pp. 66–76, 2013.

[7] H. Romero, S. Salazar, O. Santos, and R. Lozano, "Visual odometry for autonomous outdoor flight of a quadrotor UAV," in *Proceedings of the IEEE International Conference on Unmanned Aircraft Systems (ICUAS), Atlanta, USA*, 28–31 May 2013, pp. 678–684.

[8] G. V. Raffo, M. G. Ortega, and F. R. Rubio, "An integral predictive/nonlinear h control structure for a quadrotor helicopter," *Automatica*, vol. 46, no. 1, pp. 29 – 39, 2010.

[9] L. R. García Carrillo, A. E. Dzul López, R. Lozano, and C. Pégard, "Modeling the quad-rotor mini-rotorcraft," *Quad Rotorcraft Control*, pp. 23 – 34, 2013.

[10] S. Salazar, I. Gonzalez-Hernandez, J. R. López, R. Lozano, and H. Romero, "Simulation and robust trajectory-tracking for a quadrotor uav," in *Proceedings of the IEEE International Conference on Unmanned Aircraft Systems (ICUAS), Orlando, USA*, 27–30 May 2014, pp. 1167–1174.

[11] J. Alvarenga, N. I. Vitzilaios, K. P. Valavanis, and M. J. Rutherford, "Survey of rotorcraft navigation and control," Technical Report DU2SRI-2014-04-001. University of Denver, USA, Tech. Rep., April 2014.

[12] M.-D. Hua, T. Hamel, P. Morin, and C. Samson, "Introduction to feedback control of underactuated VTOL vehicles," *IEEE Control Systems Magazine*, vol. 33, pp. 61 – 75, 2013.

[13] R. Mahony, V. Kumar, and P. Corke, "Multirotor aerial vehicles: Modeling, estimation, and control of quadrotor," *IEEE Robotics and Automation Magazine*, no. 19, pp. 20–32, September 2012.

[14] S. Omari, M.-D. Hua, G. Ducard, and T. Hamel, "Hardware and software architecture for nonlinear control of multirotor helicopters," *IEEE/ASME Transactions on Mechatronics*, vol. 18, no. 6, pp. 1724 – 1736, 2013.

[15] Y. Sun, "Modeling, identification and control of a quad-rotor drone using low-resolution sensing," Master's thesis, University of Illinois at Urbana-Champaign, USA, 2012.

[16] Y.-R. Tang and Y. Li, "Dynamic modeling for high-performance controller design of a uav quadrotor," in *Proceedings of the IEEE International Conference on Information and Automation, Lijiang, China*, 8–10 August 2015, pp. 3112–3117.

[17] H. Huang, G. Hoffmann, S. Waslander, and C. Tomlin, "Aerodynamics and control of autonomous quadrotor helicopters in aggressive maneuvering," in *Proceedings of the IEEE International Conference on Robotics and Automation (ICRA), Kobe, Japan*, 12–17 May 2009, pp. 3277–3282.

[18] B. Theys, G. Dimitriadis, T. Andrianne, P. Hendrick, and J. De Schutter, "Wind tunnel testing of a vtol mav propeller in tilted operating mode," in *Proceedings of the IEEE International Conference on Unmanned Aircraft Systems (ICUAS), Orlando, USA*, 27–30 May 2014, pp. 1064 – 1072.

[19] A. Brandao, M. Filho, and R. Carelli, "High-level underactuated nonlinear control for rotorcraft machines," in *Proceedings of the IEEE International Conference on Mechatronics (ICM), Vicenza, Italy*, 27 February – 1 March 2013, pp. 279–285.

[20] "Parrot AR.Drone," Available online: http://ardrone2.parrot.com/ar-drone-2/specifications/, (accessed on 14-09-2015).

[21] "Parrot AR.Drone motor specifications," Available online: http://www.parrotshopping.com/us/p_parrot_product.aspx?i=199962, (accessed on 11-11-2015).