DATA COLLECTION FOR DEVELOPING A DYNAMIC MODEL OF A LIGHT HELICOPTER

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Abstract

At the Max Planck Institute for Biological Cybernetics the influence of an augmented system on helicopter pilots with limited flight skills is being investigated. This study would provide important contributions in the research field on personal air transport systems. In this project, the flight condition under study is the hover. The first step is the implementation of a rigid-body dynamic model. This could be used to perform handling qualities evaluations for comparing the pilot performances with and without augmented system. This paper aims to provide a lean procedure and a reliable measurement setup for the collection of the flight test data. The latter are necessary to identify the helicopter dynamic model. The mathematical and technical tools used to reach this purpose are described in detail. First, the measurement setup is presented, used to collect the piloted control inputs and the helicopter response. Second, a description of the flight maneuvers and the pilot training phase is taken into consideration. Finally the flight test data collection is described and the results are showed to assess and validate the setup and the procedure presented.

1. INTRODUCTION

In recent years, congestion problems in the transportation system have led to regulators considering implementing drastic changes in methods of transportation for the general public. One option would be to combine the best of ground-based and air-based transportation and produce a personal air transport system. A current research project at the Max Planck Institute for Biological Cybernetics aims to investigate the interaction between a pilot with limited flying skills and augmented vehicles that are part of such a system. The goal is to verify if it is possible to reach similar performance to a highly-trained pilot, also in dangerous environmental or demanding conditions. This is of great interest since one of the biggest challenges of implementing a personal air transport system is to make a vehicle as easy to fly as it is to drive a car. In this context, this work focuses on light helicopters as these best reflect the properties of a vehicle that could be used in the personal aerial transport system.

This project has been conceived as composed of three main phases. The first phase is the identification of a rigid body model of a light-weight helicopter. The second phase represents the realization of an augmented system for this rigid-body dynamic model. The third phase consists of a handling qualities evaluation to compare performance of pilots with and without the augmented system. The flight state of interest throughout the project is hover, since it is commonly considered one of the most difficult to perform as a non-expert pilot.

This paper focuses on data collection for implementation of the rigid-body dynamic model. The considered helicopter is a Robinson R44, which is a four-seat light helicopter with a single engine, a semi-rigid two-bladed main rotor, a two-bladed tail rotor and a skid landing gear. The main aim of the paper is to provide a lean and practical procedure through which reliable measurements of the control input signals and the vehicle response can be obtained for the purpose of system identification.

System identification consist of a sequence of specific steps that make possible to extract a model of a physical system from measured test data. Nowadays it is an established routine procedure in the fixed wing aircraft field for obtaining linearized rigid body equations of motion for 3 and 6 Degrees of Freedom (DoF) [1]. In the last decades, a big effort has been made for applying identification methods in the rotorcraft field [2]. In particular, the AGARD Working Group 18 on 'Rotorcraft System Identification' aimed to investigate how identification theories can be applied to rotorcraft systems. The result was a large flight-test-database obtained for three different helicopters, and the use of this database for applying identification methods and producing quasi-steady, 6 DoF and fully coupled hybrid models [3]. This study, and various others provide a rich amount of knowledge and experience, mainly related to military research [4–6].

So far, however, the performing experimental system identification for civil purposes has not been common. Expensive instrumentation technologies that are usually used for military purposes are not affordable in other fields [7]. Linked to the costs, another important aspect is the unavailability of multiple hours of test flight. The latter is needed for collecting large amounts of data, which increases the probability of obtaining reliable measurements. Furthermore, the owners of civil helicopter companies do not usually have an interest in system identification studies. The design and the development of light weight helicopters are commonly done with manual tuning and trial-and-error methods, based on previous experience. These are a few reasons why only a few studies have been performed on system identification for civil helicopters [8–10].

2. DATA COLLECTION FOR SYSTEM IDENTIFICATION

A crucial step in the system identification process is the data collection. Having reliable data is necessary to produce a final model that is close to the real physical system. The identification of the system dynamic characteristics of interest (i.e. the modes of the system) is impossible if the collected measurements do not contain information in the appropriate frequency range [11]. Three main steps need to be considered to ensure that the data collection phase provides data sufficiently reliable for identification purposes [3, 12]: the first step, presented in Section 3, involves the implementation of the measurement setup and the choice of sensors that are placed within the helicopter to measure its response. The Global Positioning System (GPS) and an Inertial Measurement Unit (IMU) are used to collect position, attitude, angular rates and linear accelerations. Four optical sensors are used to measure the input signal from the pilot (two for cyclic stick deflections, one for the collective lever, and one for the pedals).

The second step, presented in Section 4, concerns the choice of flight maneuvers. To be able to employ a frequency domain identification method, and to validate the final model, the experimental flight trials involve piloted frequency sweeps and doublets. This paper focuses on doublets maneuvers collected during initial flight tests in which the measurement setup was tested. Due to the lack of an experimental test pilot, a preliminary training phase was needed before and during flight. This ensures that the pilot is capable of performing the maneuvers safely, while obtaining reliable measurements for the identification process.

In Section 5, some flight test data is presented. In this third step of the approach, the flight maneuvers are performed for each control axis, while the pilot inputs and the system responses are measured. In the final section, conclusions are given.

3. DEVELOPMENT OF THE MEASUREMENT SETUP

This section focuses on the development of the measurement setup for collecting the input and output signals of the helicopter. First, the required measurements are described. Second, the instrumentation is presented. Particular attention is devoted to the validation of the proposed setup for the pilot input signals.

3.1. Required measurements

In order to implement an augmented system and perform handling qualities analysis, it is required to establish knowledge concerning pilot commands and the vehicle response. Therefore, it is required to measure control input positions, and the helicopter accelerations, angular rates, linear velocities and attitudes.

The flight condition under study in this paper is hover. Therefore, it is not necessary to use pressure sensors and vanes to measure velocity of the helicopter with respect to the wind. Furthermore, this project does not take into consideration measurements of the rotor's degrees of freedom.

3.2. Instrumentations for the output vehicle signals

The instrumentation for measuring the output signals of the helicopter is composed of an Inertial Measurement Unit (IMU) and two Global Positioning System (GPS) antennas. Using two GPSs makes possible to reduce ionospheric errors by modeling and combining satellite observations made on two different frequencies.

The IMU is comprised of Fiber Optic Gyros (FOG) and Micro Electrical Mechanical System (MEMS) accelerometers. The accuracy of the two GPS antennas and the stability of the IMU measurements are tightly coupled to provide a 3D navigation solution that is stable and continuous, even through periods when satellite signals are not available [1]. To enhance this function, the position of the GPS antennas with respect to the IMU needs to be known precisely (Figure 1).

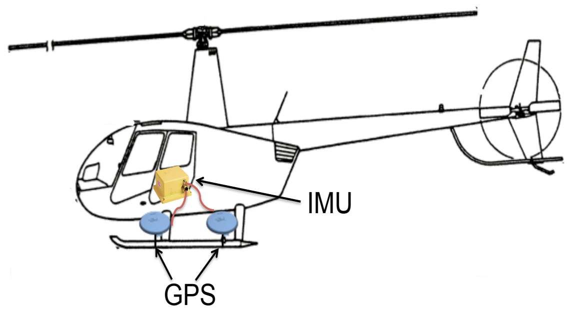

Figure 1: IMU and the GPS antennas position in the lateral view of the R44 helicopter. Modified picture from the "R44 II Pilot's Operating Handbook, Robinson Helicopter Company, 1992".

The two GPS antennas were installed on the left skid while the IMU was located close to the CoG in order to obtain physically coherent vehicle data. The location of the CoG has been determined by measuring the weight and position of instrumentation and people inside the helicopter during the flight tests.

3.3. Instrumentation for piloted control inputs

Measurements of the control displacements should be performed without affecting the pilot. Therefore, optical sensors are used that are capable of measuring a distance without mechanical contacts. The dynamic of the controls is not influenced thanks to the dimensions and the light weight ($\approx$ 44 grams) of these sensors. This aspect is very important also for safety reasons. Four optical sensors are employed to measure the displacements directly at the pilot controls (one for the longitudinal cyclic stick deflection, one for the lateral cyclic stick deflection, one for the collective lever, and one for the pedals).

3.3.1. Implementation of the measurement setup for piloted control inputs

The optical sensors can measure a distance from a specific reference object. In the considered setup, the sensors are rigidly attached to the controls, while flat surface references are located at specific distances.

[1] http://www.novatel.com/products/span-gnss-inertial-systems/span-combined-systems/span-cpt/

In this way, a continuous measure is given of the distance of a point on the controls to the reference. However, the pilot provides input to the helicopter through angular movements of the four control sticks. Therefore, the mathematical relationship should be defined between the linear distance measurements collected through the optical sensors and the angular displacements of the controls. By performing an analysis through simulations, different scenarios can be analysed for the measurement setup.

A possible scenario is presented in a schematic in Figure 2. In this scenario, the sensor attached to the cyclic stick. Three different positions are considered: the center and the two extreme positions. The most important variables are shown in the figure: l is the distance of the sensor with respect to the hinge of the cyclic, d is the distance of the reference plate and h is its height. By changing any of these variables a different relationship is obtained between the measured distance (x) and the angular displacement (α).

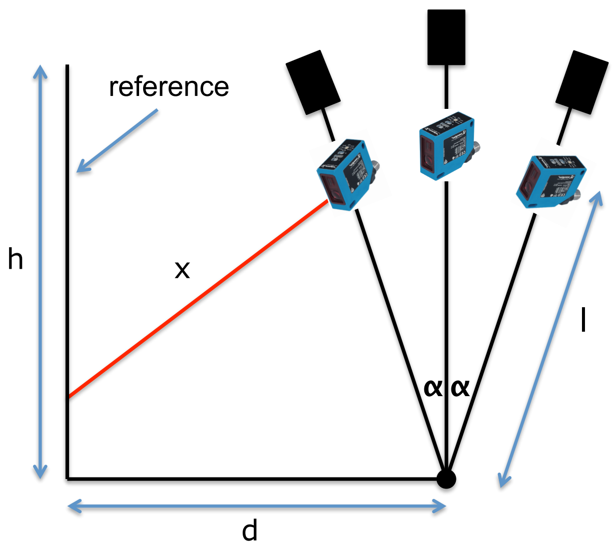

Figure 2: Schematic representation of the relation between the linear distance measurement(x) and the angular displacement (α).

As shown in Figure 3, the slope of the plate (ϕ) also plays an important role in this relationship between the measured distance x and the angular displacement α. Therefore, it is important to estimate all these variables during the calibration phase in order to make sure that the measured distances can be accurately converted into angular displacements.

As presented in Figure 3, ambiguous results are obtained in specific configurations of the measurement setup. As is shown in Figure 4, multiple angular displacements are associated with the same measured distance. This analysis has helped in avoiding bad configurations during mounting of the measurement setup. However, it is impossible to accurately determine all the variables shown in Figure 6. For this reason, the mathematical relationship between distance (x) and angle (α) was found empirically, instead of using the geometrical approach used for the simulations. This empirical method is described in the following section.

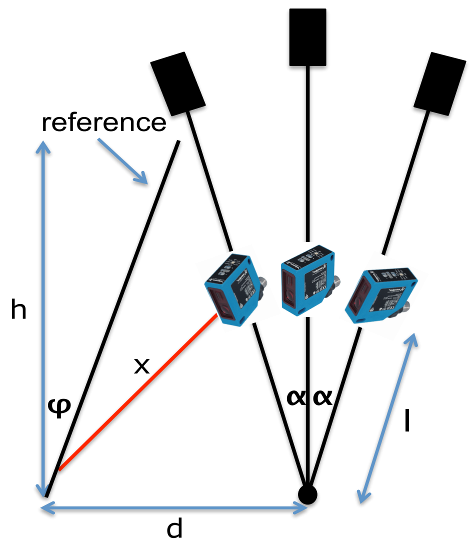

Figure 3: Cyclic bad configuration.

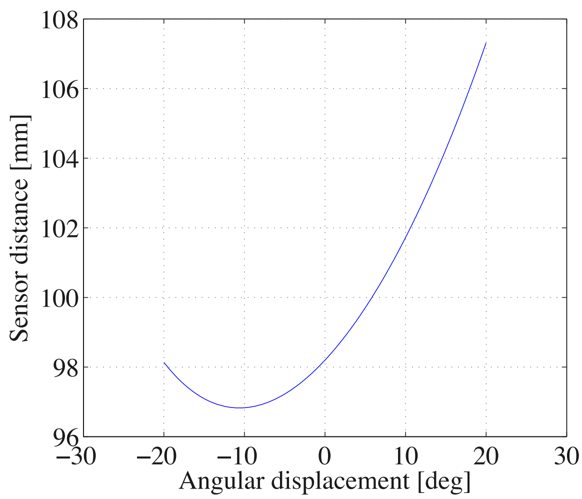

Figure 4: Measurement relationship.

3.3.2. Validation of the measurement setup for piloted control inputs

The relationship between the measured distance x and the angular displacement of the control stick α, was found using a look-up table. For each control axis, different positions were considered and variables x and α were measured. Then, the measurements were interpolated to find the final relationship. The results determined through this procedure are quite similar to the ones obtained in simulation (Figure 5). Therefore, the considerations made before through the simulations have been empirically validated and possible bad configurations have been avoided.

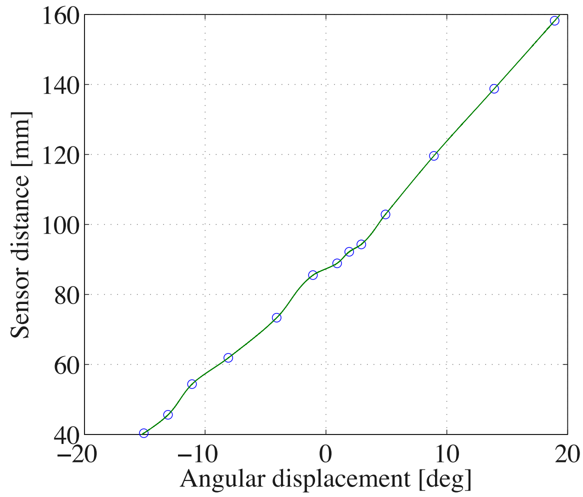

Figure 5: Relationship between the longitudinal angular displacement of the cylcic and the measured linear distance.

3.4. Sensors characteristics

The characteristics of the sensors in the measurement setup are listed in Table 1 in terms of resolutions and ranges. Given the characteristics and the limits of the performed maneuvers as presented in Section 4, the sensors are expected to provide reliable data. The choice of a proper sample rate was based on the guidelines presented in [11]. A sample rate of 100 *Hz* was chosen by considering a maximum frequency of interest of 3 *Hz*.

Table 1: Instrumentation properties

Sensor	Resolution	Range
Accelerometers[1]	0.005 m/s^2	$\pm 10\ g$
Gyro Output[1]	0.01 deg/s	$\pm 375\ deg/s$
Opt. CP24MHT80[2]	$<20\ \mu m$	40-160 mm
Opt. CP35MHT80[2]	$<50\ \mu m$	50-350 mm

[1]novatel.com/assets/Documents/Papers/SPAN-CPT.pdf
[2]http://www.wenglor.com/index.php?id=29

A schematic overview is given in Figure 6 of the final measurement setup described so far.

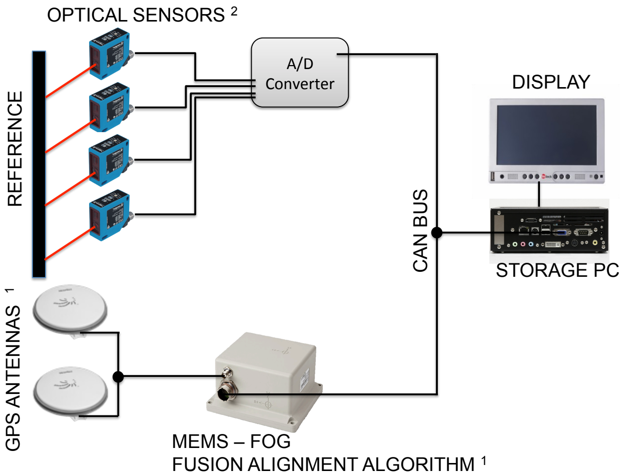

Figure 6: Schematic overview of the measurement setup with pictures from:

[1]http://www.novatel.com/products/span-gnss-inertial-systems/span-combined-systems/span-cpt/
[2]http://www.wenglor.com

4. COLLECTION OF FLIGHT TEST DATA

In this section the choice of the flight maneuvers, the pilot training phase and the collection of flight test data are presented.

4.1. Doublets

One of the common maneuvers performed during flight tests are doublets. This kind of maneuvers is generally used to validate the reliability of an identified model, while another kinds of maneuvers (e.g. frequency sweeps) are used for the identification process itself. Due to their simplicity, doublets are particularly suitable at the beginning of the training for the experimental test pilot. Their simple form can be used to perform data consistency analyses. Furthermore, the symmetry of these maneuvers permits keeping the vehicle dynamics restricted to the range of transients over which the model is expected to be valid [11].

In the helicopter identification field, it is well known that a maximum of ± 0.5 inches control pilot deflection is to be considered as an important limit [12]. These input displacements generate a change in the vehicle attitude between ± 5 and ± 15 degrees and a change in velocity of about ± 5 m/s. Generally, it is better not to perform maneuvers with a wider displacements since a big drift from the trim condition could be generated. On the other hand, smaller control amplitudes in the measurements could yield signal-to-noise ratios that are too low. Therefore, a pilot training phase was considered necessary to take these guidelines into account and to perform good and reliable doublets.

4.2. Pilot training phase

The flight condition of interest for this project is hover. It is important to be aware that many helicopters show strongly coupled degrees of freedom and are highly unstable under this condition. For these reasons it has been considered necessary to perform a preliminary training phase, on the ground and in flight, to ensure that the pilot is capable of performing the doublets safely. At the same time it must be ensured that measurements are sufficiently reliable for the identification process.

The following training phase has been performed. First, a theoretical description of the specific maneuvers was given to the pilot to make him aware of the kind of movements he had to perform for each control axis. Then, a training was conducted on ground to coach the pilot to perform maneuvers with correct input timing and magnitude. Finally, the same maneuvers were performed in flight right before the actual flight tests. The training period was important because of the lack of an experienced test pilot.

4.3. Flight tests

This section focuses on the collection of data during doublet maneuvers. The flight test had a duration of about 30 minutes. It was divided into four trials, one for each control axis. During each trail, several doublets were performed in hover conditions at 10 meters above the ground, and thus in ground effect. The weather conditions were good with a temperature of 22 degrees Celsius, a density altitude of 239 meters and wind velocity of 2.1 m/s (≈ 4 kn).

The plots in Figure 7 show the longitudinal axis input of the cyclic and the related outputs obtained from a doublet maneuver. The control input is given in degrees after mapping the measured linear distance measurements into angular displacement of the stick, as described in Section 3. The primary responses of the vehicle to the longitudinal control input are the linear velocity (u), the pitch rate ($d\theta/dt$), the pitch angle (θ) and the change in position respect to the longitudinal axis (x) of the body frame.

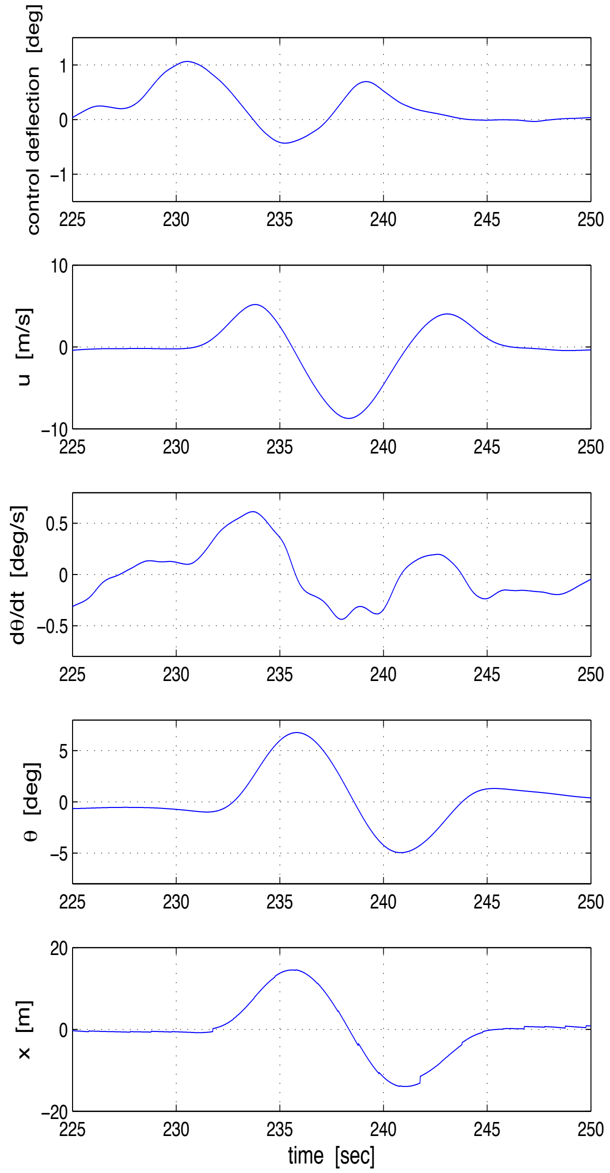

Figure 7: Doublet for the longitudinal axis of the cyclic stick.

As can be noticed, the maneuver limits presented in Section 4.1 are satisfied. However, the measurements clearly show that the pilot tried to perform the maneuvers by focusing on the helicopter responses instead of paying attention primarily to the input movements, as performed during the training phase. This could have been determined by the presence of visual references on the ground, since the flights were performed in ground effect. The result is a helicopter movement characterized by a doublet shape, while the inputs are not exactly as expected. This aspect was analyzed together with the pilot after the test flight and will be taken into consideration for the upcoming flights.

The first flight was mainly conceived for assessing and validating the measurement setup. The results of the flight trials prove that the measurement setup covers the entire range of pilot control displacements and that it provides accurate data for the helicopter response. The pilot was able to fly without being influenced by the presence of the sensors attached to the controls. This was achieved by placing the sensors on the left pilot seat together with the flat reference surfaces related to the collective and the pedals, whereas the pilot was seated on the right side of the helicopter.

The IMU and the GPS antennas provided reliable and consistent data. Furthermore, the setup placement inside the helicopter allowed the presence of another person on board that was responsible for calling the maneuvers to the pilot and for checking on the instrumentation during the test flight.

5. CONCLUSIONS

A measurement setup was implemented to collect flight test data for a helicopter in hover conditions. Two GPS antennas and an Inertial Measurement Unit were used for collecting kinematic outputs of the vehicle. Four optical sensors were employed to measure the pilot input signals (two for cyclic stick deflections, one for the collective lever, and one for the pedals). An empirical mapping procedure was considered to find the relationship between the measured distance for the four pilot controls and the angular displacements.

Before the actual flight test, a preliminary training phase was performed before and during flight to familiarize the pilot with the test procedure. Various doublet maneuvers were collected during a first flight to test the measurement setup. The measurement data showed that the setup provided reliable results. The first training phase on ground and during flight provided important information for improvement of pilot instructions for the maneuvers of interest.

The developed measurement setup will be used to perform system identification of a light-weight helicopter in hover flight conditions. The work in this paper has indicated that the main considerations for such an exercise consist of proper pilot instructions and training for the required flight test maneuvers. Subsequent work will focus on using augmentation approaches to enhance the response of the identified helicopter dynamic model and evaluating handling qualities and human performance in piloted closed-loop control tasks.

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