Initial Tuning Procedure for Attitude and Vertical Movement Controllers in Multirotor Aerial Vehicles with Heterogeneous Propulsion Units

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Abstract: In this paper, a hybrid procedure of tuning the control structure of a newly developed multirotor aerial platform is presented. Such situation presents a demanding task because there are no initial parameters of PID controllers ensuring safe flight conditions. Most methods base on full mathematical models which can be divergent from the real plant and require a process of detailed system's identification. The second area of solutions utilises different types of test benches to perform trial and error tuning in safe conditions. A method presented in this article comprises a hybrid approach connecting both practices. The key element in this solution is a model of the implemented propulsion system and physical parameters of the airframe itself obtained from the CAD software. System noise variances are gathered from experiments on the test bench and implemented in appropriate simulations. Next, the optimisation can be executed to gather parameters for every constituent controller. Finally, verification in real conditions is performed. The presented method was used for the development of two significantly different multirotor UAVs during the pre-flight PID control tuning phase. An approach is versatile for both symmetrical and unsymmetrical heterogeneous airframes.

1 INTRODUCTION

Over the past decade, micro multirotor aerial vehicles became very popular in research and commercial applications, mostly because of their flight characteristics. New solutions concerning propulsion systems and airframe designs are developed constantly. Along with increasing complexity and demands of UAV applications, more sophisticated aerial platforms with plenty of the on-board equipment are introduced. However, more payload requires extended lift capability, which is usually achieved by increasing power and size of propulsion units. Unfortunately, a significant rise of the UAV mechanical outline prevents flights in closed or indoor spaces. An exemplary solution for this problem is the introduction of coaxial propulsion into the micro UAV technology, which increases maximum thrust and payload lift capabilities within the same physical size (Bondyra et al., 2016). For some designs, the process of optimising the payload capabilities and flight time efficiency leads to usage of heterogeneous, non-symmetrical propulsion systems. Example of such structure is the *Kruk* UAV described further in this paper.

While there is a great flexibility in designing and arranging motors and propellers for particular UAV design, every divergence from classic, symmetrical quarto-/hexa-/octo- copter scheme results in the more demanding control strategy. There are several, well researched approaches to control of a multirotor aerial platform: attitude, attitude with altitude hold and position control. Different flight controllers, especially the custom ones, are equipped with various control algorithms, starting from attitude ((Bouabdallah and Siegwart, 2007), (Dikmen et al., 2009)), vertical movement ((Gąsior et al., 2016a), (Connor et al., 2017)) or overall position ((Gasior et al., 2017)). However, in every case of the newly developed UAV, the problem of initial tuning of its controllers arise. This essential for the proper in-flight operation of the UAV task has to be performed in a very cautious way in order to reduce risk to the operator or equipment.

In addition, flexible and universal tuning procedure is very useful for the further exploitation of the UAV, i.e. during significant payload rearrangement, development of different control methods or adaptation to varying flight conditions.

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2 RELATED WORK

In general, there are three methods of initial tuning of controllers for multirotor aerial platforms. The first solution is based on the expert knowledge of the team of engineers and parameters obtained during development of previously constructed vehicles. If there are no major differences in the airframe design and propulsion setup, there is a high probability that a new design will require only some minor, in-flight tuning. This is a situation very common in development projects, where new iterations of market products are released. However, there may be differences not only in physical parameters and performance but in mechanical vibrations due to use of different materials and specific aspects of structural design. It is a well-known issue leading to errors and inadequacies in the state estimation which automatically leads to failure in the control process. To sum up, even in this approach it is recommended to test platform in the test stand before carrying out free flight experiments.

The second method depends on the complete mathematical model of the developed platform. Unfortunately, it is hard to utilise such model for newly constructed UAV, while there is no data to tune the model itself. Sometimes the sub-models are used to simplify this process. In such case, the problem is divided into several simpler simulations, i.e. concerning single axis of rotation. In addition, noise in sensor readings has a great impact on control quality as well. Therefore, there is a requirement to perform noise levels trimming.

Third approach utilises various test benches ((Panizza et al., 2016), (Bondyra et al., 2017), (Hoffmann et al., 2010), (Tayebi and McGilvray, 2006)), which allow performing tuning process in safe, laboratory conditions without the risk of damaging the equipment in-flight. In addition, this method is based on the trial and error technique. Without reaching into the details of mathematical modelling, parameters are chosen on the basis of rules corresponding to the type of the applied control technique. This process can also be automated which leads to the reduction of tuning time (Wang and Poksawat, 2017) (Howard, 2017). It has to be mentioned, that platform during the tuning process on the test bench can change its physical characteristics, since fixing the UAV in test rig influences mainly the vibration levels in comparison to the in-flight performance. Test bench usually dampens vibrations due to the dispersion in extended mechanical structure. Therefore, during the real flight tests, noise amplitude can be significantly higher, disturbing state estimation and flight control. Another important issue with fixing the UAV to the stationary bench is the introduction of friction in axes of rotation. Omitting this phenomenon causes higher overshoot during flight attitude stabilisation.

Every mentioned approach has its own advantages and disadvantages since there is no perfect routine. A hybrid and flexible method described in the next section constitutes the novel and safe approach to selecting initial parameters of the flight controllers with the high success rate preserved.

Proposed tuning process was used in various modifications of the control algorithm in the *Falcon V5* platform and during initial tuning of the *Kruk* UAV. Both vehicles, shown in the Fig. 1, are quite different in the terms of size, payload capabilities and configuration of the propulsion system. The *Falcon V5* UAV was developed as an indoor research aerial platform with extended lift capabilities. It is equipped with 8 motor-propeller sets arranged on 4 symmetrical arms in the coaxial configuration. Such approach allowed to achieve up to 6kg of maximum thrust force within 2.7kg of the UAV's own mass. Payload capabilities reach up to 1kg of equipment with the flight time of 12 minutes. On the other hand, the *Kruk* UAV is designed as asymmetrical hexacopter with heterogeneous propulsion system consisting of four single units and two double, coaxial ones. This UAV has the ability to lift several kilograms of payload with the flight time extended up to 40 minutes. However, both vehicles were successfully developed, tuned and tested thanks to the procedure described in this article.

3 METHOD DESCRIPTION

The proposed method is based on a fusion of previously mentioned solutions. It uses simple models of propulsion units, gathered from the test bench, and physical information about hardware from the CAD software. This approach, connected with experimental verification on the rotary test stand, results with increased safety of tuning process, especially with high thrust platforms.

As mentioned above, the first element of the procedure is a model of the propulsion unit. It is developed on the basis of measurements from the propulsion analysis system presented in (Aszkowski et al., 2017) showed in Fig. 2. This test rig provides measurements of thrust, reaction torque, angular velocity and power consumption in relation to the duty cycle of the control signal. Such equipment is especially useful in case of coaxial propulsion units, which are way harder to model in a mathematical manner. Sensors of the propellers' angular velocity are rarely available on the multirotor UAVs, therefore all models have to

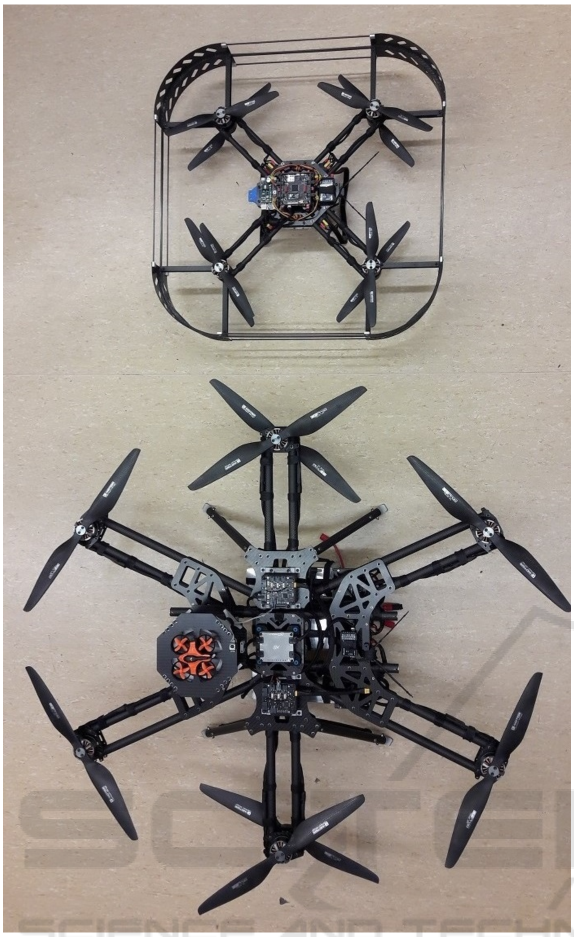

Figure 1: Comparison of *Falcon V5* (upper) and *Kruk* (lower) UAVs.

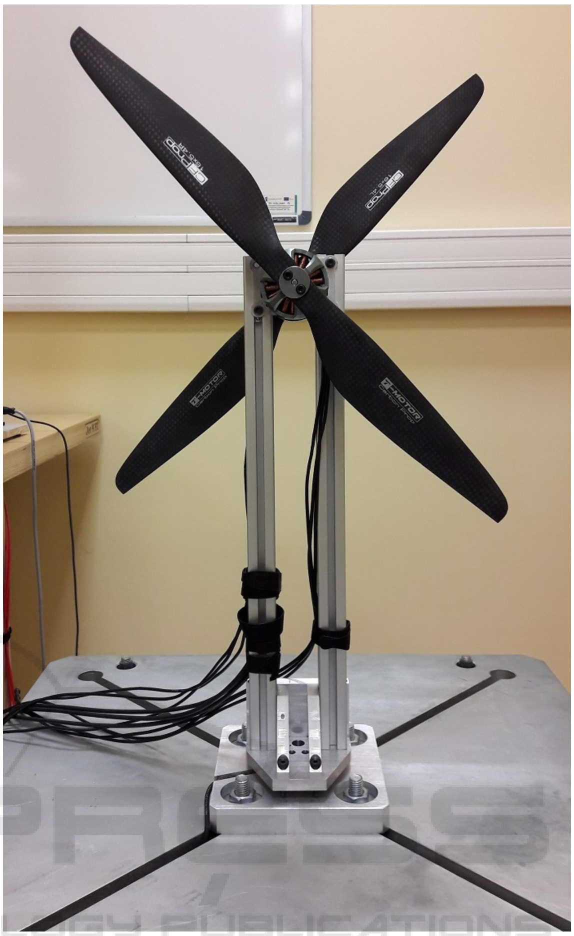

Figure 2: Propulsion analysis system used in modelling process.

be based on the duty cycle of PWM signal as a control input.

Next step is a simulation development phase. Firstly, it is performed separately for each sub-controller (Roll, Pitch, Yaw rotation and vertical movement). Then, the simulation is extended into the full attitude and vertical movement control. At this point, dependencies between controllers are taken into consideration. In the developed simulation, some additional blocks are required. First one is a preset signal generation block which delivers operator command inputs to the second block - control algorithms. Finally, data acquisition and presentation block is required to compare tuning results. In rotation and movement model section, there are parameters defining noise amplitude on the output signals, which highly affect the performance of control algorithms. Those parameters have to be estimated, but it is better to marginally overestimate than underestimate. In this step, tuning of mentioned controllers is performed with manual or automatic techniques.

Next step is an experimental verification on the test stand. This phase allows to correct noise parameters and fit simulation to the real environment if needed. If propulsion unit models were formulated correctly and physical parameters of the structure remained unchanged, selected parameters should allow the platform to maintain stability. This stage is usually performed for Roll and Pitch axes because it is the most popular configuration of rotary test benches. Moreover, it is hard to construct the test stand with rotation about Yaw axis and changing altitude, which would have a negligible effect on the platform movement.

After those steps, full movement simulation can be utilised and all parameters of controllers can be modified to meet desired performance. In this step, vibration parameters should be slightly increased to eliminate the dampening effect of the test stand. It is important to tune controllers in a cautious manner, because too aggressive parameters in the real environment may cause instability. It is important to mention, that on every step of simulations or experimental verification it is possible to implement corrections in parameters to adapt to the real behaviour and meet stated requirements. Summary of the proposed method was shortened into following points:

1. Physical CAD modelling of multirotor UAV;
2. Propulsion units experiments on the test rig;
3. Development of models of propulsion units;
4. Formulation of separate simulations for each movement axes;
5. Implementation of controllers and tuning process;
6. Experimental verification of simulation on the test stand;
7. Correction of tuned parameters (optional);
8. Formulation of full attitude with vertical movement simulation;
9. Correction of tuned parameters (optional);
10. Experimental verification during free flight tests;
11. Correction of tuned parameters (optional).

4 MODELLING OF PROPULSION UNITS

In a majority of mathematical models, the thrust force generated by propulsion unit is represented by Eq. 1.

$$F_i = b_i \cdot \omega_i; \quad (1)$$

where: F_i - force generated by $i-th$ propulsion unit, b_i - scaling factor, ω_i - angular velocity of a propeller. This method is applicable only to single propulsion units, which makes harder to represent coaxial setup with tractor-pusher propeller pair. In addition, in most cases, no information about the rotational speed is available in the most UAV sensory systems. Therefore it has to be omitted and extracted from the PWM control signal, as the *ESCs* (*Electronic Speed Regulators*) keep the blade velocity constant in relation to the control signal.

Tests were performed on the thrust analysis system (Aszkowski et al., 2017) for propulsion units dedicated to both considered platforms. Based on gathered data, models were formulated. Thrust model of units implemented in *Falcon V5* platform was developed in (Gąsior et al., 2016b). The same procedure was applied to the ones mounted in *Kruk* UAV. Block diagram of mentioned modelling method is shown in Fig. 3. Two duty cycle signals and supply voltage measurements are processed by Takagi-Sugeno fuzzy system, which calculates the thrust. The same method was used in modelling of the reaction torque of coaxial propulsion unit, which is essential to develop the simulation of Yaw movement. However, thrust and reaction force for single propulsion units were approximated by two dimensional polynomial ($x-y$, duty cycle - voltage, with orders for each axis of 3 and 1 respectively).

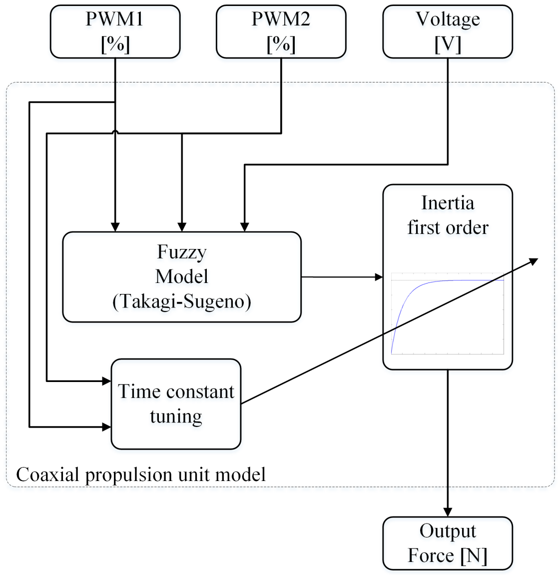

Figure 3: Block diagram of a coaxial propulsion unit model.

5 SIMULATIONS

As stated earlier, there are four main areas of developed simulations during described tuning workflow:

- Roll and Pitch;
- Yaw;
- Vertical movement;
- Roll, Pitch, Yaw and vertical movement in one.

Separated simulations for each axis are formulated with the Euler's dynamics equation of a rigid body:

$$\tau = \mathbf{I}\alpha + (\omega \times \mathbf{I}\omega), \quad (2)$$

where: τ - applied torques, α - angular accelerations of the body, ω - angular velocities of the body and I - the matrix of moments of inertia. Formulation for angular accelerations is gathered after several operations:

$$\alpha = \mathbf{I}^{-1}\big(\tau - (\omega \times \mathbf{I}\omega)\big). \quad (3)$$

Reducing above equations to single axis ($\omega_y = \omega_z = 0$ and $\alpha_y = \alpha_z = 0$ in case of an X axis) is following:

$$\alpha_x = \frac{\tau_x}{I_{xx}}. \quad (4)$$

Torques are calculated from forces generated by each propulsion unit and distance from selected symmetry axis:

$$\tau = \sum_{i=0}^{i<n} d_i \cdot F_i, \quad (5)$$

where: n - number of propulsion units, d_i - distance of propulsion unit from rotation axis and F_i - force generated by i-th propulsion unit. Positions of each propulsion unit is gathered from CAD model along with moments of inertia. Symmetric axes, if possible, are located the same way as an on-board AHRS (Attitude and Heading Reference System). Torque around Yaw axis is calculated from the Eq. 5 with reaction forces generated by each propulsion system and planar distances to them.

The general method of the single axis simulation development was presented in (Gasior et al., 2017), where tuning process of cascade controllers for *Falcon V5* platform was performed. In the same paper, the adequacy of simulation has been proven for the stated platform. As it has been mentioned in Sec. 3, the first phase of initial tuning is a development of separate simulations for Roll, Pitch, Yaw and vertical movement. This usually comes down to calculating angular or vertical acceleration based on generated thrust and double integrating to gather velocity and position. Fusion of this method along with additionally required blocks merges into the full simulation. Simulation results of the rotary test bench for the *Kruk* platform with a comparison to the experimental data are shown in Fig. 4. Presented case is performed on tuned parameters, which also have been used in real experiment. This example validates the possibility to tune controllers on the basis of simulation. As can be seen, tracking quality is satisfactory and squared error characteristics are very close between two presented cases.

After tuning and validating controllers in all mentioned axes separately, there is a need to merge all of them into the one system. The overall block diagram of all four simulation components is presented in Fig. 5. Preset signals are artificially generated or recreated from recorded flight sequences and passed to the control block. This section is responsible for calculating appropriate control signals for propulsion units. The control structure is design-dependant and should be identical to the one implemented in avionics software. The output of this block consists of eight duty cycle signals which are also design-dependant. In *Falcon V5* and *Kruk* platform there are always eight motors implemented, divided into four or six propulsion unit respectively. Next step is a calculation of generated thrust and reaction force, which are thereafter transformed into angular and vertical accelerations based on physical parameters from CAD model. Finally, double integration in both cases allows gathering velocities and positions. In each output, the noise is added to adapt them to real conditions. These signals close the loop for the implemented controllers. Every simulation is executed with the frequency equal to the refresh rate of a control loop in the main on-board controller.

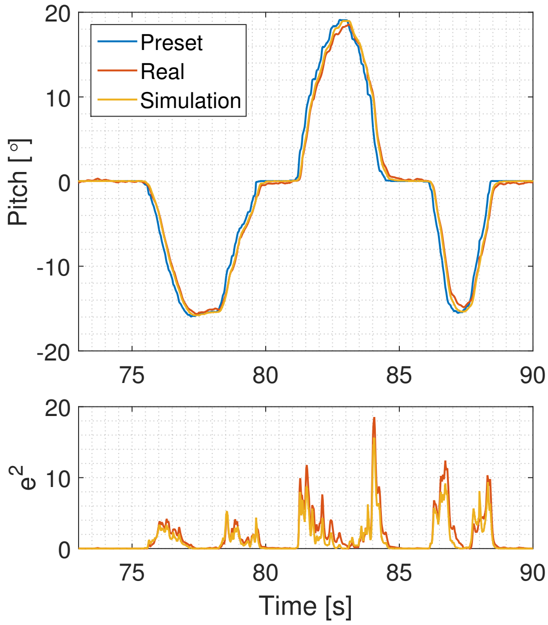

Figure 4: Results of the control performance of platform *Kruk* in Pitch axis during simulation and real experiment on the test bench.

Tuning process should be performed sequentially, one controller at a time. Parameters selected in the individual simulations should be used as initial ones in the merged simulation. Experimental verification is described in the following section.

6 EXPERIMENTS AND TUNING RESULTS

With the fully developed and tuned simulations, the next step is to conduct experimental validation. The first phase was performed on the rotary test stand showed in Fig. 6. This device fixes the UAV movement and reduces degrees of freedom to only one rotational axis. In this configuration, Roll and Pitch controllers can be validated. Exemplary characteristics from one experiment with *Kruk* platform are presented in Fig. 4, where Pitch axis was concerned. As can be seen, the controller has a good performance and maintains tracking during the whole sequence. The squared error remains within reasonable limits. The

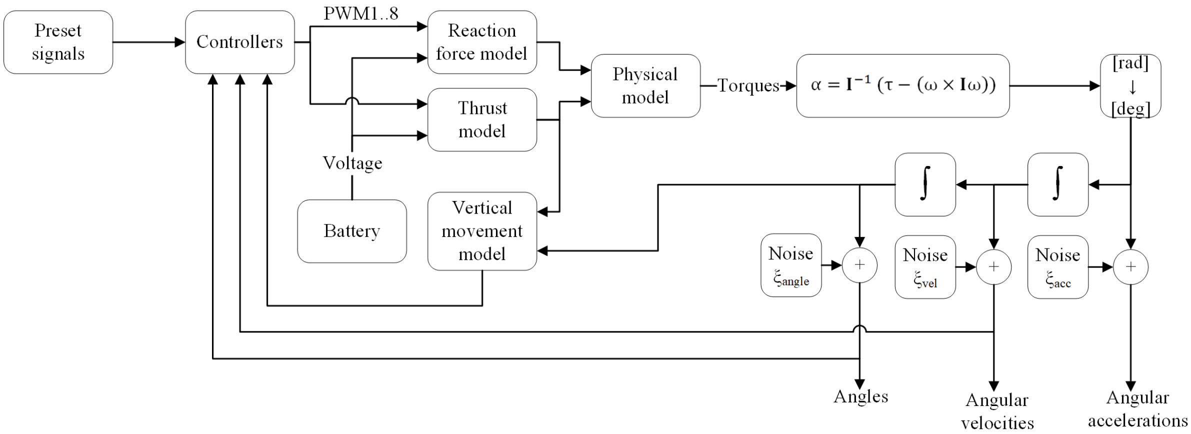

Figure 5: Block diagram of Roll, Pitch, Yaw and vertical movement simulation.

Figure 6: Platform *Kruk* mounted on the test stand in Pitch axis.

highest points in error characteristics are present during rapid changes in preset signal, where controllers' response is slightly slower.

After positive verification on the test bench, the oncoming step is a free flight experiment performed in order to check the performance of the Yaw and vertical movement controllers. It is advised to implement them sequentially, firstly Roll, Pitch and Yaw with throttle control, and finally with vertical movement turned on. This approach reduces the number of possible errors during implementation and allows to locate them more accurately. Three characteristics from exemplary free flight are presented in Fig. 7, 8 and 9, representing Roll, Pitch and Yaw respectively. Controllers with parameters selected during the simulation phase managed to correctly track preset signal which was very dynamic because of a characteristic of the performed mission. Errors in all three examples were comparable, but the highest divergence has been observed in Yaw controller. This could be the result of wind gusts during flying through corridors.

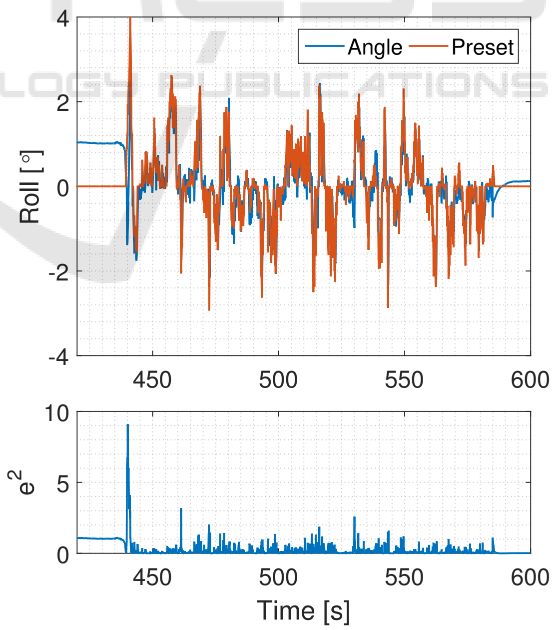

Figure 7: Results of the control performance of platform *Kruk* in Roll axis during real flight.

Experiments on controllers of vertical velocity has been performed in (Gasior et al., 2017) for *Falcon V5* platform. Unfortunately, these experiments have not been completed so far for the *Kruk* UAV.

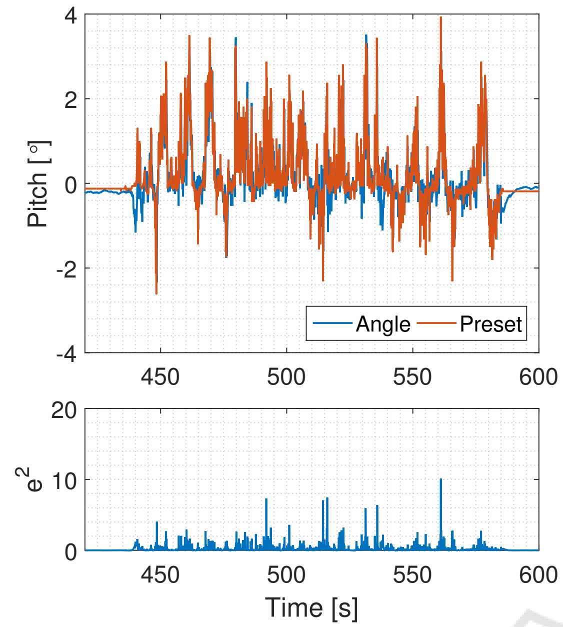

Figure 8: Results of the control performance of platform *Kruk* in Pitch axis during real flight.

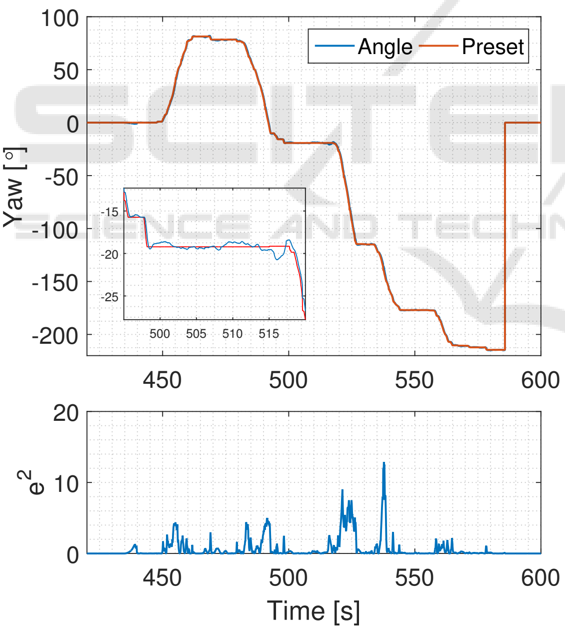

Figure 9: Results of the control performance of platform *Kruk* in Yaw axis during real flight.

7 CONCLUSIONS AND FUTURE WORK

Presented method of initial tuning of the controllers' parameters proven itself in real life scenarios. It was tested during modification of control scheme for the *Falcon V5* platform and initial tuning for the *Kruk* UAV. It is important to mention, that the complete model of analysed multirotor UAV is not required to achieve satisfactory results. This affects the development time, which can be reduced by eliminating the calibration process of the mentioned model.

One of the key points of the described method is a model of propulsion unit, which is the foundation to all of the simulations. Thanks to its flexibility, this method is extremely useful to simulate unsymmetrical platforms with heterogeneous propulsion units.

In the future work, authors plan to finish the experimental verification process of the vertical movement controller for the *Kruk* UAV. Moreover, comparison with state-of-the-art initial tuning techniques will be performed. Finally, automatic tuning algorithms for different types of controllers will be implemented to simplify comparison process and parameterise tracking performance with an adequate cost function.

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