# IoA Experience on Aerial Delivery

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## *ABSTRACT*

*This paper presents some selected results of the project SKY MULE which is conducted in the Institute of Aviation (IoA) in Warsaw. The aim of this research is to design and construct an automatic trajectory controller for an unmanned parafoil and payload system to make it usefull for precise aerial delivery tasks. SKY MULE's payload is composed of two connected but separable modules: the control module consisting electronic and electro - mechanical equipment, and cargo module (various dimensions and shapes of that module are allowable). SKY MULE's motion is controlled by two control cords being operated by electro – mechanical servo - actuators with DC motors and PWM controllers. Example results of laboratory tests carried on these units is presented. Control unit is designed with PC-104 computer as a central sub-system. It is provided with software for pre-programming the site of destination and flight trajectory. The attention is focused mainly on robust control algorithms designed to assure stable realization of SKY MULE's desired trajectory, even for large changes of system parameters, occured due to different shapes and parameter changes of cargo modules. Feedback signals are provided by measuring unit based on MEMS - type sensors integrated with GPS receiver. The system is controlled in two alternative modes: autonomously, by automatic system, or remotely, by a human operator.*

## 1.0 INTRODUCTION

Problems of precise aerial delivery appeared in the *Institute of Aviation* in Warsaw (*IoA*) some years ago as an idea of unmanned parafoil and payload system named *SKY MULE* [6], [8]. This system was planned to be controlled in two alternative modes: autonomously, by automatic system, or remotely, by a human operator. Thus, general idea of the project was to design and construct an automatic flight control and trajectory stabilizing system for *SKY MULE*'s mission. Basic structure of this vehicle is depicted on Figure 1 with the following denotations: $\{E,N,H\}$ - reference system being in quiescentstate towards the Earth, $(x,y,h)$ - *SKY MULE*'s position determined in $\{E,N,H\}$ reference system, $\mathbf{V}$ - flight velocity vector, $\mathbf{V}_h$ - descending rate vector (projection of $\mathbf{V}$ onto vertical line), $\mathbf{V}_p$ - horizontal velocity vector (projection of $\mathbf{V}$ onto horizontal $\{E,N\}$ plane), $\Psi_T$ - track angle ($0 \le \Psi_T < 2\pi$). Solutions we are looking for are adapted to the typical product (parafoil) manufactured by the Polish company *AirPol Sp. z.o.o.* Typical parameters of such parafoil, determined for calm air conditions, are listed in Table 1 [8].

Motion of *SKY MULE*'s wing - shaped parafoil and payload unit is controlled by two control cords (Figure 1) being operated by two electro – mechanical actuators, each one for one control cord ("right" and "left" control signals $u_R$, $u_L$ represent lengths of right and left control cord reductions respectively). The structure of payload is modular – it is composed of two connected and separable parts (modules): the control module consisting electronic and electro - mechanical equipment, and cargo module. It is assumed that various dimensions and shapes of cargo module will be allowable.

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**Table 1: Typical parameters of considered parafoil and payload vehicle (calm air conditions).**

| PARAMETER | VALUE |
|---|---|
| Payload mass | $m_{\text{payload}} \leq 150$ kg |
| Minimal radius of a turn | $R_{\min} \approx 10$ m |
| Time needed for the turn of 180° | $t_{\pi} \approx 5$ s |
| Cruising speed (straight line flight) | $V_{p0} = \lvert \mathbf{V}_{p0} \rvert \approx 10$ m/s (average) |
| Rate of descent (straight line flight) | $V_{h0} = \lvert \mathbf{V}_{h0} \rvert \leq 4$ m/s (average) |
| Control signals range | $u_R, u_L \in [0, 0.75]$ m |

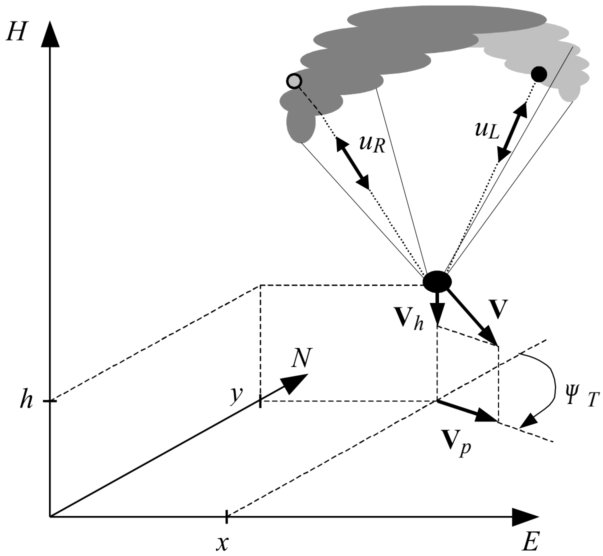


**Figure 1: System *SKY MULE* – basic parameters (control cords are denoted by dotted lines with arrows $u_L$, $u_R$ representing "left" and "right" control signals).**

## 2.0 CONTROL MODULE

The control module consists of four sub-systems (units): actuators unit (with two actuators), control computer, measuring unit, and powering unit (the set of batteries). Simplified structure of this module is depicted on Figure 2 where batteries are neglected and only one actuator is presented for simplicity.

Measuring unit (block ***M***) is designed to provide feedback signals for automatic control system. Eight signals are measured: track ($\Psi_T$) and heading ($\Psi$) angles, geographical position: latitude ($\phi$) and longitude ($\lambda$), angular velocity of yawing motion ($r$), altitude ($h$), velocity ($V$), and static pressure ($p_S$). Five of them ($\Psi_T$, $\phi$, $\lambda$, $h$, $V$) are obtained by means of *GPS* receiver being the sub-system of measuring unit. Angular velocity of yawing motion ($r$) is measured by *MEMS* - type gyroscope (*Analog Devices*), and static pressure ($p_S$) – by *MEMS* - type pressure sensor (*Motorola*). Magnetic course ($\Psi$) is measured by electronic compass designed and constructed in the Institute of Aviation. The set of Hall - effect magnetic field sensors is used in this unit as sensing element. Gyroscope, pressure sensor and compass are connected to the set of 12-bit analog – to - digital converters via anti - aliasing filters (sampling frequency is set at 50 Hz). The measuring unit was built and succesfully tested on several types of objects, *e.g.* small unmanned airplane [7] and patrol & rescue hovercraft [3].

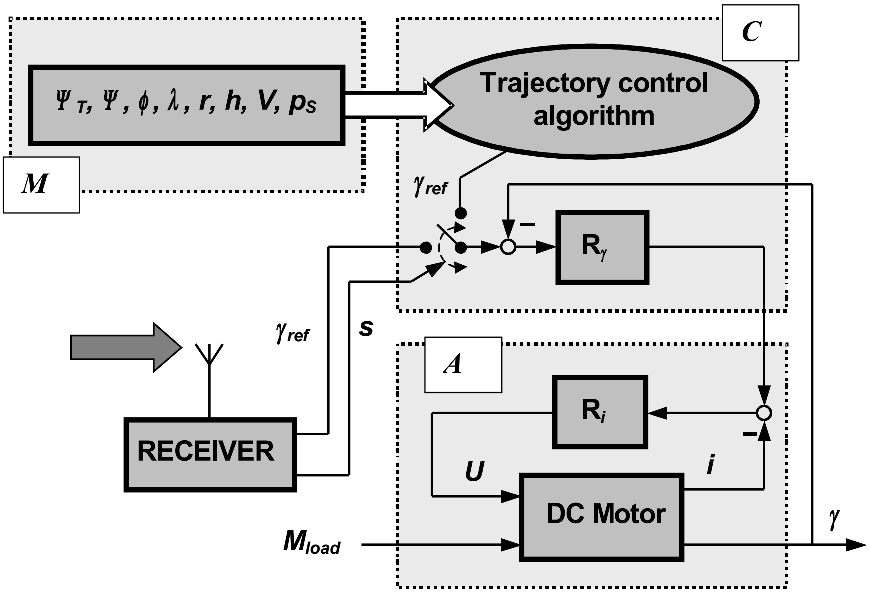


**Figure 2: Simplified structure of the control module.**

Each cord used to control *SKY MULE's* motion is operated by the electro - mechanical servo - actuator provided with *DC* motor (block ***A***). The signal $M_{load}$ depicted on Figure 2 represents the external torque affecting the actuator due to control cord reaction. Motion of the motor's shaft is converted into the linear displacement of control cord by the gear composed of rack wheel meshed with rack belt. Some details of this mechanism are presented on the picture (Figure 3), where gear's lid is removed to make the meshed elements visible. One end of the rack belt is fastened to the end of control cord while the other end of this belt is mechanically and electrically (limit switch) protected from getting off the gear.

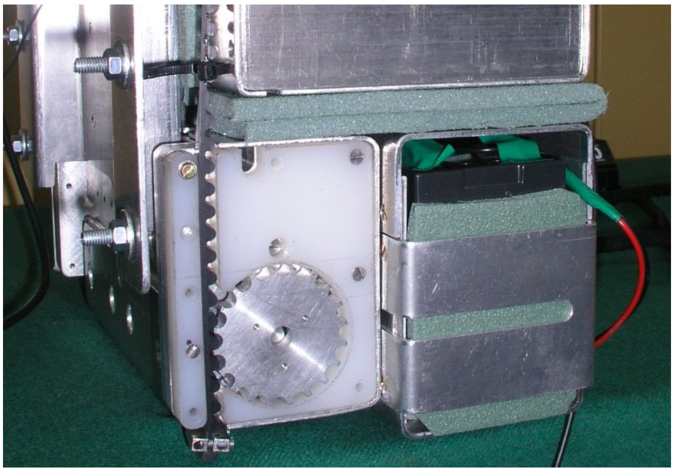

**Figure 3: Actuator's gear - rack wheel and rack belt are visible after removing gear's lid.**

The displacement of control cord ($u_R$ or $u_L$) is thus proportional (with constant and precisely known factor of proportionality) to the angle of motor shaft's revolution $\gamma$ of respective actuator. So, $\gamma_{ref}$ , $\gamma$ denotations are used on Figure 3 instead of $u_R$ and $u_{Rref}$ (or $u_L$ and $u_{Lref}$) for simplicity – meaning remains the same.

The actuator is controlled by the current regulator ($\mathbf{R}_i$) based on pulse - width modulation (*PWM*) of voltage $U$ supplying the armature in order to obtain the desired armature current $i_{ref}$. [1], [9] This regulator is designed and constructed as the independent electronic sub-system of the actuator. The angle $\gamma$ is controlled by $\mathbf{R}_\gamma$ regulator implemented in control computer (block ***C***). This regulator accomplishes the simple control law, proportional with angular velocity $d\gamma/dt$ correction, to stabilize actuator's motor shaft motion. Feedback signal $\gamma$ is obtained by the potentiometer [6].

It is important to notice that there are two possible sources of $\gamma_{ref}$ signal representing the desired value of $\gamma$. One of them is the trajectory control algorithm, implemented in control computer and used in autonomous automatic mode of control. The second one is the on-board radio system receiving manually generated signal $\gamma_{ref}$ from the human operator. The signal denoted as $s$ and used for switching the system between "autonomous" and "manual" control modes, is transmitted the same way.

Actuators were designed and constructed in the Institute of Aviation and after that some tests were carried on in order to check their parameters and usability for *SKY MULE* project. One of such results is presented below (Figure 4). This is the actuator's response to the excitation (desired position of the rack belt) generated manually. The shape of exciting signal is typical for the "manual" mode when a human operator controls the system remotely generating the reference signals manually. There was no external load affecting the rack belt during this experiment ($M_{load}$ = 0).

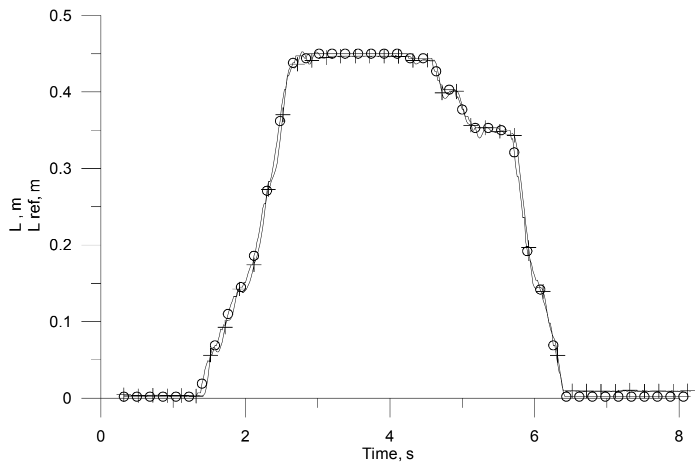


**Figure 4: The result of manual excitation of the actuator. "Crosses" marked curve - the actual position of actuator's rack belt (*L*), "circles" marked curve – manually generated signal representing the desired position of this rack belt ($L_{ref}$).**

Curves from Figure 4 are so close together that the difference between them is not visible clearly enough. It is presented on another diagram (Figure 5) showing the time pattern and range of control error.

*PC-104* computer (block ***C***) was chosen as a central sub-system of control unit. It was provided with software for performing several tasks - the most important of them are listed below:

- Mission planning: pre-progmamming the site of destination and desired trajectory of flight;

- Desired trajectory stabilization – on-line computation of desired course and transforming it's value into desired position of servo – actuators (right $\gamma_{R(ref)}$ and left $\gamma_{L(ref)}$ respectively);
- Execution of $\mathbf{R}_{\gamma}$ control law assuring actuator's stability and close tracking of $\gamma_{R(ref)}$, $\gamma_{L(ref)}$ signals.

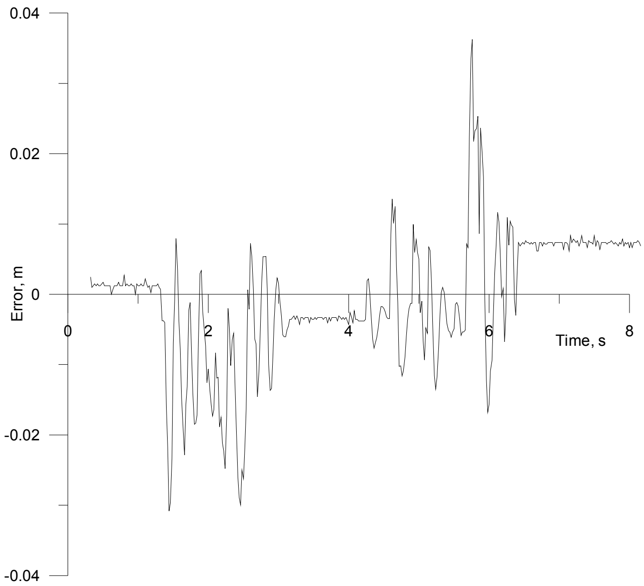


**Figure 5: Control error for the result depicted on Figure 4 – the difference *L* - *L*ref.**

Units discussed above were designed and constructed in the *Institute of Aviation* and then tested. Some of them (actuators) in laboratory, some (measuring unit, control computer) in flight tests on small *UAV* [7]. Some tests were also performed on patrol & rescue hovercraft *PRP-560* "*Ranger*" which is designed and manufactured in the *Institute*. Results of these experiments were used as the basis for identification of dynamic characteristics of this vehicle [3]. The module is provided with the set of batteries (voltage: 12 V, capacity: 15 Ah). Finally the housing was constructed and the control module was assembled (Figure 6). Outer dimensions are 300×280×180 mm and total weight 15 kg. Now this module is ready for flight tests.

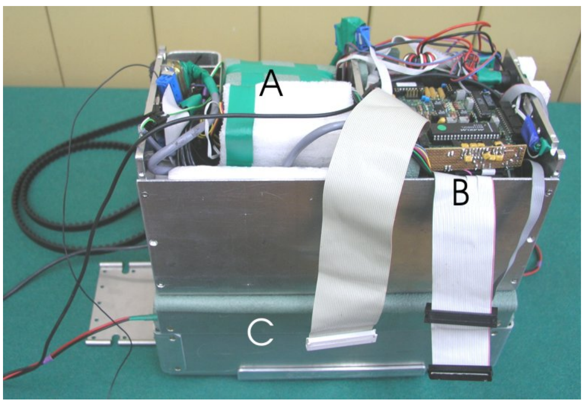


**Figure 6: The control module with removed lid of the housing and control computer (section B) taken out. Measuring unit is installed in section A and actuators with batteries in section C.**

# 3.0 HEADING (COURSE) CONTROL

Mathematical modelling of parafoil and payload objects' flight dynamics is rather a complex and difficult task leading to sophisticated models composed of sets of nonlinear differential or integro - differential equations and considerable identification tasks. Solutions of these problems are difficult and, first of all expensive, because of large number of experiments indispensable to obtain satisfactory results. Therefore we focused our efforts on robust control algorithms and simple control laws assuring directional stability of *SKY MULE*'s motion even if a crucial discrepancy between *a priori* known models and behaviour of the actual object occurs.

We are going to design the system assuring stability of the desired heading angle tracking that can bear large changes of system parametrs, occurred for example due to different shapes and other parameters of cargo modules. Structure of one of possible solutions is depicted on Figure 7, where $K_r$, $K_\Psi$, $h_r$, $h_\Psi$, $u_{R(\max)}$, $u_{L(\max)}$ represent constant parameters of the controller, $A_R$, $A_L$ – left and right actuators transfering electrical input signals into linear displacements $u_R$, $u_L$ of control cords. Block denoted as ***M*** represents the measurement unit providing electrical feedback signals of measured and/or estimated quantities, and $\Psi_{ref}$ represents the desired heading angle (course). Dead zone $h_\Psi$ is proposed to prevent the controller from "too nervous" reactions to the control error. This solution is applied succesfully in many autopilots (for airplanes and ships). Dead zone $h_r$ is proposed to limit the influence of the noise in $r$ signal. As a matter of fact this signal is filtered in measuring module (like other measured signals), but it is obtained from *MEMS* - type sensor, so the problem of noise influence is essential. Both controller gaines $K_r$, $K_\Psi$ and other parameters are expected to be precisely tuned experimentally during flight tests. The structure presented below is slightly simplified so some details are neglected. However it should be pointed out that the control error $\Psi_{ref} - \Psi$ should be prevented from exceeding absolute values greater than 90° (π/2 rad.). One of possible ways to do that is to use the *arc tangent* function to compute the control error and replace the simple summing operator from Figure 7 by the following one:

$$\varepsilon_\Psi(\tau) = arctg\left[\Psi_{ref}(\tau) - \Psi(\tau)\right] \quad .$$

Of course, the *arc tangent* function can be replaced by every smooth, monotonically growing, and antisymmetric, function $f$, which tends to $\pi/2$ when the argument tends to $+\infty$, and tends to $-\pi/2$ when the argument tends to $-\infty$.

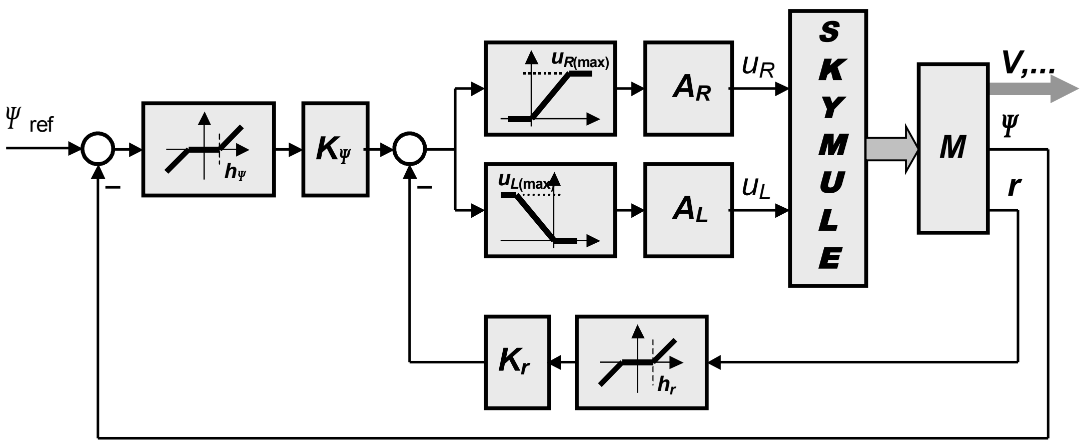


**Figure 7: A proposition for heading controller's structure.**

Presented structure was in - flight tested on small unmanned airplane (of a mass about 20 kg and 2 m wing span) [7]. Results obtained during these tests are encouraging and satisfactory. Considered parafoil and payload unit for *SKY MULE* system is expected to be stable in yawing motion. Mathematical model of this motion (linearized and limited to four state variables: pitch and yaw angles and their time derivatives) has one real negative pole, two complex conjugate poles with negative real parts, and one real pole with zero value. Proposed structure seems to have enough potential to stabilize such process.

We are also taking into account more sophisticated solutions like predictive control algorithms discussed in [11] or approaches proposed for systems with the essential unstructured uncertainties [2], [5]. Some of them are based on functional analysis results [4] and seems to be too conservative, but other are interesting because of their potential to deal with the extreme level of mathematical model uncertainties [13]. We are planing to test these propositions by simulations after an identification process. For the first flight trials the simple and robust solution proposed above seems to be the safest.

## 4.0 TRAJECTORY CONTROL

It is assumed that the projection of *SKY MULE*'s desired flight trajectory onto horizontal plane $\{E,N\}$ is composed of straight line segments connected one after another to form a broken line. An attitude of every segment is represented by it's heading angle $\Psi_{tr}$ (determined unambigiously due to the strictly specified direction of desired motion along each segments). The desired heading angle for *SKY MULE* vehicle is then determined as $\Psi_{ref} = \Psi_{tr} + \varepsilon_{\Psi}$ (Figure 8), where $\Psi_{tr}$ represents the heading angle of desired trajectory segment being currently tracked, and $\varepsilon_{\Psi}$ represents a correcting term that depends on a distance $\Delta L$ between *SKY MULE* and this segment. This distance is measured by means of *GPS* receiver and the sign of $\Delta L$ variable is defined by the following rule: $\Delta L > 0$ when *SKY MULE* has to turn to the right to get closer the desired trajectory, and $\Delta L < 0$ otherwise.

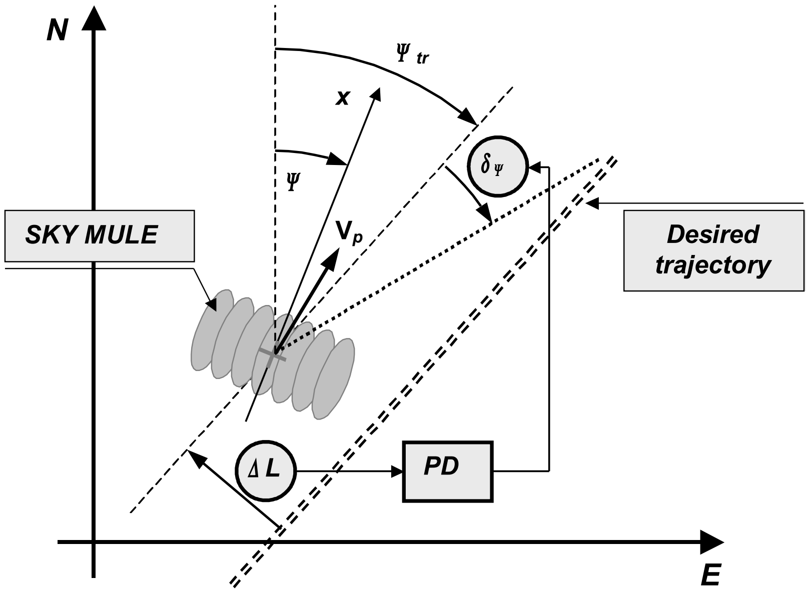


**Figure 8: Trajectory control – definition of correcting term $\delta_{\Psi}$ for desired heading $\Psi_{ref}$.**

The simple and effective way to stabilize the tracking process is to adapt well known *PD* control law with the term $\varepsilon_{\Psi}$ defined by the following formula:

$$\delta_{\Psi} = k_L \Delta L - k_{DL} \frac{d\Delta L}{dt} \quad ,$$

where $k_L$, $k_{DL}$ are constant parameters. Due to well known difficulties with the estimation of time derivative of $\Delta L$ (*GPS* measured value of this signal is discontinuous), a techniques of time delay control [12], [14] are adapted. Thus the equation presented above in every time moment $\tau$ takes the form:

$$\delta_{\Psi}(\tau) = k_{L1} \Delta L(\tau) - k_{DL1} \Delta L(\tau - \delta) \quad ,$$

where $k_{L1}$, $k_{DL1}$ are constant parameters (of course different from $k_L$, $k_{DL}$) and $\delta$ is a constant time - delay.

Proposed solutions (heading and trajectory controllers) were tested as the structure for marine autopilot [10]. Results obtained by simulations and experiment were satisfactory and the structure seemed to have quite good potential to deal with model uncertaities, perturbations and even wide discrepancies between the mathematical models and actual control object. Moreover, the simple structure with only several parameters will easier to adjust during experiments. This makes us almost sure that the decision to use this structure in first flight tests is the safest and the most reasonable.

## 5.0 CONLUSIONS

Presented discussion shows the current status of the project *SKY MULE* conducted in the *Institute of Aviation* in Warsaw. All solutions discussed here belong to the process which is not ended up till now, so some of them may change in nearest future. The control module of the system is ready for flight tests which are planned to start in late autumn 2006. These tests are believed to give an opportunity to verify some new and alternative ideas prepared for control system modifications (predictive or adaptive control) and a deeper insight into refinements of such object's dynamics.

The idea of simple, not expensive, and effective system for precise aerial delivery is expected to be interested for the army and some civilian institutions too. We are looking for partners (in Poland and abroad) sharing our interest in solutions for precise aerial delivery. The future of the project depends on potential purchasers interested in exploitation and development of such systems, so we are also looking for new areas where our system can by effectively used.

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