Ergonomic Remote Control Technique for Horizontal Rotors Equipped UAVs

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Abstract—**This paper presents an ergonomic remote control technique based on using IMUs (Inertial Measurement Units) both on helicopter and human hand. This technique provides a new remote control method for horizontal rotors equipped UAVs (Unmanned Aerial Vehicles). The neurobiological aspects and inspiration are also presented. In our experiments, we compared different types of remote control interfaces using a modified DraganFlyer IV quadrotor helicopter which adequately represents the universal mathematical model for that kind of flying vehicles called PVTOL (Planar Vertical Take-Off and Landing) problem. Different metric-based comparisons verify that using the IMU based interface even beginners can better control the helicopter.**

I. INTRODUCTION

In the past few years, growing scientific interest surrounds the UAV robots. Autonomous airplanes that are able to navigate without a pilot may carry out important tasks in circumstances where human presence is either dangerous or not possible. Such areas may include solving the Mars exploration tasks of NASA, or rescue errands that are dangerous for humans [1], [2].

Navigating a helicopter is a task similar to keeping a ball made of steel on a marble table only by changing the steepness of the table. Scientific results using different approaches show that navigation is soluble by different methods in specific flying tasks [3], [4]. Perfect automation is not solved yet, and in many tasks, an operator navigates the airplane equipped with many different sensors by remote control.

Usually, learning to navigate a model helicopter by remote control takes weeks or even months. Using these ubiquitous human-machine interfaces needs great routine. The problem is not only the consequence of nonlinearity, but acquiring the complicated motoric transformations until it becomes an automated process is also part of the learning process.

All of the different model helicopters, researchers often examine the problems of the four-rotor and the horizontal-rotor helicopters [5], [6], [7]. It is safe and relatively simple to navigate a four-rotor small sized helicopter even in a laboratory [8], [9]. Our goal was the realization of a remote control that makes people able to navigate aerial vehicles safe without much learning.

Several fields in robotics require adequate remote control methods to facilitate the human-machine linkage. One of the most important from these areas is the field of teleoperation [10], which continually intends to develop better and better remote control methods. The teleoperation of NASA Robonaut [11] measures the position and orientation relative to the base using PolhemusTM, six DOF tracking system. For fixed-wing UAVs, similar to our work, comparisons have been done before [12], where the altitude joystick proved to be the most effective remote control instrument.

In our study, we compared different remote control techniques, considering their neurobiological aspects. Based on these considerations, the validity of the designed system was tested in both simulation and real environments.

The structure of this paper is as follows: after the introduction, the second chapter introduces the theoretical background, especially unmanned aerial vehicles, planar vertical take-off and landing problem, PID controller stabilization inertial measurement unit and the summary of related neurobiological aspects. The third chapter gives an overview of three types of remote controls. The fourth chapter contains the experimental framework, including both software and hardware parts. In chapter five, experimental results can be found. Chapter six gives the conclusion.

II. THEORETICAL BACKGROUND

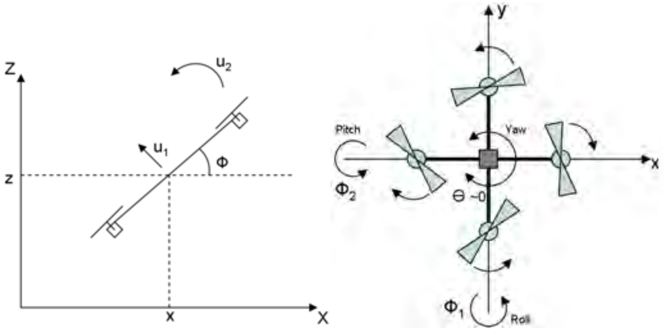
A. *Unmanned Aerial Vehicles (UAVs)*

Present days robotics and robotic applications gain ground world-wide. Unmanned Aerial Vehicles are generally applied in terrain surveillance, but not only this type of application can be observed. They can be the basis of survivor questing in a disaster or high voltage wire auditing. In our case we focus on horizontal rotor based aerial vehicles and robots, eg. one rotor plus auxiliary rotor helicopters. They are usually operated on more or less the same principles. The main fact is that they are fundamentally unstable without sensorial control and the lateral acceleration - the second derivative of position -

is determined by the tilt of the vehicle. The tilt as quantity consists of two components, the roll and the pitch angles. These two angles are the base of the control, too. Therefore it is important to identify the mathematical model to carry out the control equations.

B. Planar Vertical Take-Off and Landing Problem

Focusing on our quadrotor experiments, the most practical mathematical model is the Planar Vertical Take-Off and Landing (PVTOL) problem. This model is motivated by the need to balancing stabilization of rotorcrafts which are able to take off vertically like helicopters and some special airplanes [13].



(a) (b)

Figure 1: In Fig.(a) dynamical model of PVTOL can be seen. Origin of coordinate system, placed in the center of the helicopter is depicted in Fig.(b).

In two dimensions equations of this nonlinear dynamic system can be written as follows:

$$\begin{gathered}\ddot{x} = -sin(\phi) \cdot u_1 + \epsilon \cdot \; cos(\phi) \cdot u_2 \\ \ddot{z} = cos(\phi) \cdot u_1 + \epsilon \cdot \; sin(\phi) \cdot u_2 + 1 \\ \ddot{\phi} = u_2\end{gathered}$$

where x and z are the horizontal and vertical displacement, ϕ is the tilt angle of the rotorcraft shown on Fig. 1a. u_1 is the collective input and u_2 is the difference between lifting forces produced by two rotors. ϵ is a small value which characterizes the rolling moment and lateral acceleration. The term -1, which represents the acceleration, acts in order to normalize the gravity. The main thrust is the sum of the thrust of each motor. This model clearly describes our four rotor aircraft in two dimensions. This can be expanded to 3D if we consider the heading of the object stabilized to be zero. In general, a 3D rigid object can be described with 6 coordinates (3 for position and 3 for orientation) in our case we consider 5 coordinates, since the heading is specified. Although we have 4 independently controlled motors, the system is still underactuated.

It is clear that this model can not be stable alone, and this suspicion can be proved mathematically with the help of Lyapunov stability analysis [14].

Table I: Main physical effects acting on a helicopter.

Effect	Source	Formulation
Aerodynamic effects	Propeller rotation, bouyancy C - constant Ω - angular velocity	$C\Omega^2$
Counter torque	Change in rotation speed J - constant	$J\ddot{\Omega}$
Gravity effect	Center of mass position	mg
Gyroscopic effects	Change in orientation of the rigid body Change in orientation of the propeller plane Θ, Φ - angular offsets Ω_r- rotor angular velocity	$I\Theta\Phi$ $J\Omega_r\Theta, \Phi$
Friction	All helicopter motion	$C\dot{\Phi}, \dot{\Theta}, \dot{\Psi}$

C. Dynamical model

In the case of the applied 3D model, we can consider the following assumptions valid, since their effect is negligible:

- The frame and other structural elements can considered to be rigid.
- Symmetrical structure
- Centre of gravity coincides with origin, which can be found in the centre of the frame
- Propellers are also rigid
- The thrust produced by a propeller is proportional to the square of the rotating velocity of the propeller.

Using the above assumptions, the dynamic equations of the system can be written into a standard nonlinear state-space model (see, e.g. [15]) where the generalized coordinates are $q = (\psi, \theta, \phi, x, y, z)$, where (x, y, z) denotes the position of the center of mass of the helicopter relative to a fixed intertial frame and (ψ, θ, ϕ) are the Euler angles (yaw, pitch and roll, respectively) that describe the orientation of the structure. The whole state vector of the model is $x = (q, \dot{q})$, thus, it is 12 dimensional. The physical inputs of the system are the individual rotor speeds. For our control purposes, a linearized version of the original nonlinear model is sufficient in the usual form:

$$\dot{x} = A_c x + B_c u \tag{1}$$

where $x \in \mathbb{R}^{12}$ and $u \in \mathbb{R}^4$. The controller have been designed for this model.

D. Stabilization with PID controller scheme

During the experiments it became clear that the pilot cannot keep the helicopter in stable horizontal position by himself, therefore software and sensors are needed that are functioning with higher sampling rate than a human is able to follow with eyes and control by hands. This means that the stable horizontal position should be supported by the help of a tracking control algorithm. Besides the assumptions discussed above, we can simplify our model by assuming that sampling frequency is high enough to let us handle the change of tilt angles as linear quantities, so we assume that starting the system from a perfectly horizontal stable position, we can linearize the motion equations around the equilibrium. This makes the design of the control structure much easier. Among the linear controllers, one of the most frequently used is an

LQ-servo controller that is fairly easy to design and is known to have advantageous robustness properties.

The state equation of a discrete-time version of a linear system (1) can be written as follows: $x_{k+1} = Ax_k + Bu_k$, where x_k and u_k are the state vector and the input of the system at time instant k, and A and B can be directly computed from A_c and B_c assuming zero order hold on the input. One of the significant parts of the LQ controller is the cost function, which we would like to minimize by feedback: $J = \sum_{k=0}^{\infty}(x_k^T Q x_k + u_k^T R u_k)$ where Q and R are positive definite symmetric weighting matrices (tuning parameters). The resulting feedback is a linear full state feedback of the form: $u_k = -Kx_k$, where $K = (R + B^T PB)^{-1} B^T PA$ and P could be gained from solution of the following discrete-time Ricatti algebraic equation:

$$P = Q + (A^T PA) - (A^T PB)(R + B^T PB)^{-1}(B^T PA)$$

Let the controlled outputs of the system be given in the following form: $\omega_k = Ex_k$, where $E \in \mathbb{R}^{l \times n}$. To get a controller that is appropriate for the quasi constant non-zero reference values as well, we can add - similar to the continuous time solution - integrating effect to the control loop by introducing the following equations: $z_{k+1} - z_k = r - \omega_k$, where r is a (piecewise) constant reference to be tracked. This way, the original x state vector can be completed with a $z \in \mathbb{R}^l$ state sequence.

It can be seen that if the system is stabilized (e.g. by an LQ controller), then $z_{k+1} - z_k \to 0$, which means that $r - y_k \to 0$, that is $y_k \to r$, if $k \to \infty$. In this case, the feedback gain K for the extended system can be computed in the following way:

$$u_k = -K \left[\begin{array}{c} x_k \\ z_k \end{array} \right] = -K_x x_k - K_z z_k, \qquad (2)$$

where $K_x \in \mathbb{R}^{p \times n}$, and $K_z \in \mathbb{R}^{p \times l}$. Focusing on the four rotor helicopter: $\omega = \left[\begin{array}{ccc} x_1 & x_2 & x_3 \end{array} \right]^T$.

The following values were obtained for K_x and K_z:

$$K_x = \begin{pmatrix} 1.2583 & 0.3793 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1.2583 & 0.3793 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0.5036 & 0.1517 \end{pmatrix}, \qquad (3)$$

$$K_z = \begin{pmatrix} -0.1708 & 0 & 0 \\ 0 & -0.1708 & 0 \\ 0 & 0 & -0.0684 \end{pmatrix}$$

From the sparse structure of the gain matrices, it is easy to see that the LQ optimal controller is essentially a PID feedback, where matrix K_x contains the proportional and derivative feedback gains, while matrix K_z contains the gains of the integral terms.

Fig. 2 shows the control loop, where the PID controllers (Roll, Pitch, Yaw) actuate the rotors based on the signals of the IMU, while the operator modifies the input of the controllers and the thrust. Without feedback, the helicopter would turn upside down in less than a second.

Let us denote the parameters of each PID loop as follows:
- proportional term: $p_t = K_p \cdot E_t$
- integral term: $i_t = K_i \cdot E_t + i_{t-1}$
- derivative term: $d_t = K_d \cdot (E_t - E_{t-1})$

where $E_t = X_t - R_t$, where X_t is the measured value at time instant t, R_t is the reference value at time instant t, K_p, K_i, K_d are constant coefficients which determine the strength of each term. The output value is the sum of the three terms:

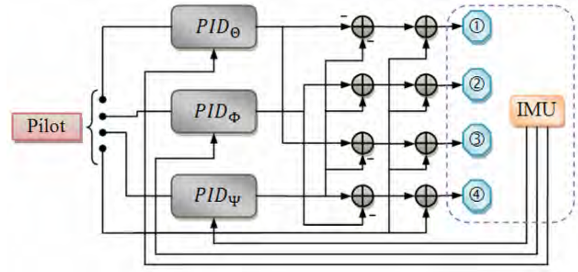


Figure 2: PID control loop, the PID controllers (Roll, Pitch, Yaw) actuate the rotors based on the signals of the IMU, while the operator (pilot) modify the input of the controllers and the thrust.

$$y_t = p_t + i_t + d_t$$

This control scheme was capable to keep the rotorcraft in stable horizontal tilt position, but this was not enough to avoid all lateral displacement. This is the main task of the person who controls the vehicle. In some cases, the heading should be slightly corrected manually since the angular rate is controlled.

E. Inertial Measurement Unit

To measure tilt angles, we used IMUs (Inertial Measurement Units) [16]. This small unit has three types of sensors, MEMS gyroscopes, accelerometers and magnetometers. A sensor fusion algorithm is applied to merge data. Gyroscopes measure the angular rate, accelerometers and magnetometers give accurate static angular reference. We can reliably measure pitch and roll angles and the derivative of yaw. Therefore no other sensors are needed to satisfy the requirements of the PID controller which is then able to keep the rotorcraft in stable horizontal orientation. In our experiments we used MTi Motion Tracker from Xsens Motion Technologies (Fig. 3).

F. Neurobiological aspects and inspiration

The motor system of human is very complex and able to produce graceful movements. When the pilot controls an airplane or a helicopter, it takes all his or her attention to focus on the visual feedback. Sophisticated, amazing and mysterious connection between the occipital lobe, the motor cortex and the muscles make up a system that is able to generate purposeful movements.

1) Muscle spindles: Primary feedback comes from the muscle spindles which detect the contraction and extension of muscles. These small somatosensory units let us know the state of muscles, thus it gives feedback of the force or position through spinal tracks. Although, these sensory units provide information, precise movements can only be achieved by visual feedback.

2) Control framework: The general setup of the remote control of a flying device looks like the following: a person - the pilot-holds the remote control and looks towards the aircraft which is hovering or passing by. In this paper the camera-equipped, video-controlled aircrafts are not discussed because they are beyond the scope of this paper.

3) Pose-related approach: The displacement of horizontal rotor equipped flying vehicles is highly related to its tilt angles. It is a well-known fact that when a person tries to imitate the motion of a rotorcraft, he or she uses his/her hands to show the angle of the vehicle. The reason is that the minimum number of somatosensory feedback loops with the most similar tilt behavior can be represented by hand movements. Therefore if someone would like to show the state of the rotorcraft, the hands will be used with extended fingers to imitate this.

4) Ergonomic interface: The approach above popped up the idea to create a remote control device which measures the tilt of the hand and provides reference from it.

III. REMOTE CONTROLS

In this section, three types of remote control interfaces will be discussed. Two of them are usual in the view of commercial radio controlled model aircrafts. The third one is a tilt sensor system which is unconventional to be used as a helicopter remote control.

A. Most usual interface

In one of our experiments we used a Futaba Skysport T4YF remote controller (Fig. 3). Devices like this usually have two rods which can be moved with the left and the right thumb. The left rod controls the thrust and the yaw angle while the right one controls the tilt angles. As it can be read on many forums over the Internet, nobody can control a four rotor helicopter with this control for the first time, after practising weeks or months develops the ability to hold the aircraft in stable position. This device has an output interface which can be used to connect it to a PC.

Figure 3: On the left side: Futaba Skysport T4YF remote controller http://www.futaba.com/. In the middle: Logitech Attack 3 joystick http://www.logitech.com/. On the right side: Xsens Motion Technologies' MTi IMU http://www.xsens.com/.

B. Joystick

The joystick was the second interface that was tested. The Z-axis controller on the back of the base was assigned to thrust. Axes X and Y controlled the roll and pitch angles and the yaw angular rate can be controlled by the two side buttons on the top of the stick.

C. Xsens MTi IMU

From the biological approach described above we decided to measure tilt position of the hand with Xsens MTi device. (Fig. 3) It was tied on the upper side of the right hand with elastic tape. Reference angles were measured by this IMU and the yaw angle and thrust are controlled by the left hand with the joystick's buttons and Z-axis respectively.

IV. FRAMEWORK

As mentioned previously, the rotorcraft control system consists of a remote controller device, a person who holds it and the rotorcraft itself which can also be separated to fundamental parts: processor circuitry, sensor and propulsion system. In this section we will describe the original framework of a DraganFlyer IV and the modified framework built to satisfy the requirements of our experiments.

A. The original DraganFlyer IV

DraganFlyer IV is a four-rotor RC model helicopter. Stabilization is done by a microcontroller which is connected to three perpendicular piezoelectric gyroscopes. One of the rotors is marked by yellow adhesive stripe while the others have red stripes. The yellow one indicates the front of the helicopter. Two opposing rotors rotate clockwise while the others rotate counter clockwise to cancel yaw rotation and make the yaw angle controllable by the pilot. The original remote controller is a Futaba T4YF which is described in the section above.

B. Modifications to the original DraganFlyer

The original DraganFlyer was not versatile enough to satisfy the needs of our experiments, so we did some modifications. It was clear that we had to replace the original controller circuitry to prepare the device for custom motor control, sensor set, and communication. The new printed circuit board is equipped with PIC18F4431 microcontroller unit, power MOSFETs and RS232 communication interface (Fig. 4a). Then the new helicopter is completed with an Xsens MTi inertial measurement unit. Power is supplied by two wires to decrease weight. Main control and stabilization tasks are done by software on PC.

A 'hard limit' potentiometer is integrated to avoid motors speeding up too high on controller or communication failures. Using this equipment with appropriate software we managed to achieve stable horizontal position. Only thrust, yaw angle change and lateral displacement should be controlled by the pilot.

V. EXPERIMENTAL RESULTS

In this section our experimental framework will be introduced. Then the measurement results and a comparison will be presented.

A. *Experiment setup*

The rotorcraft was placed in the center of a rectangle drawn on the floor and a camera was fixed on the ceiling (Fig. 4b). The task of the pilot was to fly the rotorcraft and to try to keep it in the center of the rectangle as accurately as he could. The camera was connected to an other PC and a MATLAB script was taking the pictures and was tracking the helicopter. We asked some students from the university to fly our rotorcraft. The demographics of the participants: age between 20 and 24 years, male, university students, non of them is any of the authors. They have not had any helicopter remote control practice before the experiment except the fourth one who has been trained with Futaba for months. The order of remote control method probably did not influence the result, because a beginner needs at least daily half or an hour practice for three weeks to be able to keep the helicopter safely in the air. We also decided to do the experiments in the following order: Futaba, IMU, joystick, and Futaba again to show that there was no significant learning during the process.

In the experiment, the flying height was between 5 and 30 cm. The power of thrust was a fix parameter, this value did not need any control in the experiments after take off because of the ground effect (evolved air-cushion) and higher flying was neither reasonable because of safety (the participants were beginners). The resolution of the sensitivity were 8 bits between -31 degree and 31 degree at all three remote control devices.

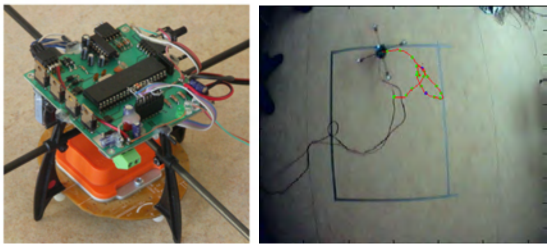

(a) (b)

Figure 4: In Fig.(a) PCB replacement of the original DraganFlyer can be seen. Experiment setup and rotorcraft tracking is depicted in Fig.(b).

B. *Experiments with Futaba T4YF*

The first flight was controlled by the Futaba remote controller. As it was expected, nobody could fly securely without practising weeks or months. The results are shown on Fig. 5 left and Fig. 6 top.

It was hard to keep the rotorcraft inside the rectangle, we can say that only professionals can be successful with it.

C. *Experiments with joystick*

Flights with joystick seemed to be much better. The role of the control of the yaw angle linked to right hand which might be the reason for better results which can be seen on Fig. 5 middle and 6 middle.

D. *Experiments with Xsens IMU*

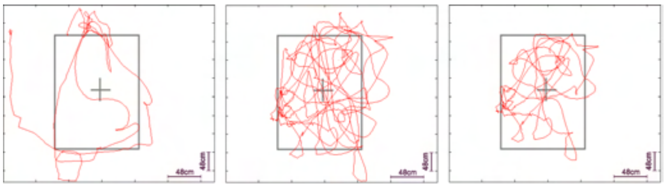


Figure 5: Flight trajectory with Futaba remote control (left), joystick (middle), Xsens IMU (right)

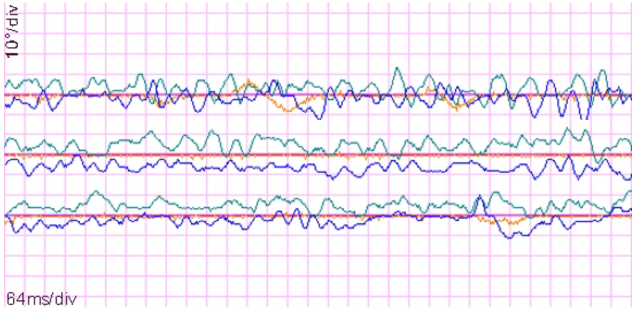


Figure 6: Roll, Pitch and Yaw angles (vertical axis) vs. Time (horizontal axis) in Futaba experiment (top), joystick experiment (middle), Xsens experiment (bottom)

As it can be seen on Fig. 5 right and Fig. 6 bottom, the best results were produced with IMU attached on hand (Fig. 7). Inspecting the measured values, we found that surely anyone can fly our rotorcraft more or less securely without any practice this way. These results let us suppose that other horizontal rotors equipped vehicles could be controlled like this as well.

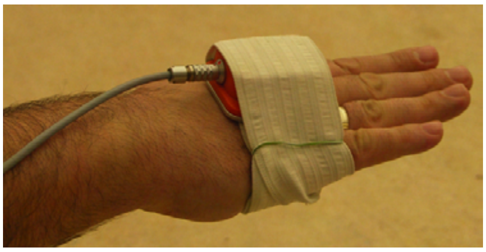


Figure 7: Experimental setup of IMU attached on hand.

E. *Evaluation*

The following result evaluations had been done: we measured the distance between the center of the square and the position of the helicopter. Based on these data we evaluated the RMS (root mean square) and deviation of the points. We also calculated the rate of the position points inside and outside of the square. The results can be seen in Table II.

Table II and Fig. 8 show that the researchers achieved better results when they used the angle of the hand as reference, as compared to the other two methods. It can be seen that the

Table II: Statistics of measurement, data are normalized to the sides of the rectangle. Min: minimal excursion, Max: maximal excursion, Mean: mean of excursion, Dev: deviation, Pts: number of measurement points, Out: number of measurement points out of the rectangle, the percentage of the outdoor points is given also.

		1. person	2. person	3. person	4. person	Mean
M	Futaba	0.0692	0.08	0.1701	0.2075	0.1317
i	Joystick	0.0559	0.1236	0.3449	0.0289	0.1383
n	Xsens	0.0231	0.2482	0.2008	0.1631	0.1588
	Futaba2	0.1049	0.0289	0.1126	-	0.0821
M	Futaba	3.4005	2.6932	2.7864	2.1369	2.7543
a	Joystick	1.81	2.6318	2.5953	1.8852	2.2306
x	Xsens	1.1841	1.6508	2.1792	1.7543	1.6921
	Futaba2	2.4968	2.1662	1.9596	-	2.2075
M	Futaba	1.3791	0.9574	0.9088	0.9266	1.0430
e	Joystick	0.8188	1.1333	0.9927	0.6624	0.9018
a	Xsens	0.4886	0.8433	0.9159	0.8266	0.7686
n	Futaba2	0.8897	0.9758	0.7364	-	0.8673
D	Futaba	0.9504	0.4872	0.4777	0.4789	0.5986
e	Joystick	0.4496	0.5564	0.4814	0.3532	0.4602
v	Xsens	0.2493	0.2906	0.3882	0.3594	0.3219
	Futaba2	0.7145	0.5454	0.3527	-	0.5375
P	Futaba	152	235	148	150	-
t	Joystick	165	195	127	223	-
s	Xsens	247	224	202	224	-
$[Pcs]$	Futaba2	128	221	118	-	-
O	Futaba	68 45%	58 25%	22 15%	33 22%	27%
u	Joystick	45 27%	63 32%	25 20%	23 10%	22%
t	Xsens	5 2%	14 6%	72 36%	43 19%	16%
$[Pcs]$	Futaba2	12 9%	63 29%	11 9%	-	16%

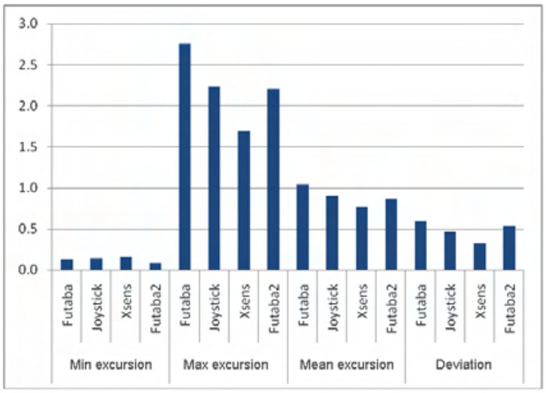


Figure 8: Average excursion values from statistics of measurements.

second Futaba experiment did not give a significantly better result, therefore no essential learning occured during the time of the experiment. This, however, could be foreseen, as it needs several months of regular practice to handle the helicopter safely. These experiments support that by measuring the angle of the hand, learning time can be significantly reduced, and a safer control can be realized by this method. Moreover, it is likely that using our method, better results could be attained with other types of helicopters as well, as compared to using other controlling methods.

VI. CONCLUSION

In this paper we discussed the general helicopter framework, comparison of different types of remote control methods and their biological aspects. In spite of these subjective experiments we made sure that the best method for controlling horizontal rotor equipped UAVs is when the pilot just imitates the tilt of the rotorcraft with his/her hands. The reason for this is the advance of natural movements and the lower number of somatosensory feedback loops.

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