2016 14th International Conference on Control, Automation, Robotics & Vision
Phuket, Thailand, 13-15th November 2016 (ICARCV 2016)

Modeling and Control of a Hexacopter with a Rotating Seesaw

Dolev Yecheskel
Department of Mechanical Engineering
Ben-Gurion University of the Negev
Beer-Sheva, Israel
email: dolevye@post.bgu.ac.il

Shai Arogeti
Department of Mechanical Engineering
Ben-Gurion University of the Negev
Beer-Sheva, Israel
email: arogeti@bgu.ac.il

***Abstract*—This paper presents a novel multicomputer type with a unique structure. This structure allows decoupling angular motion from translational motion along one of the body axes, and by that, five of the body degrees of freedom (DoF) can be controlled independently. The proposed aerial vehicle is a hexacopter with six propellers, such that four propellers are attached to the vehicle body and the other two attached to a seesaw. The seesaw is free to rotate around a single axis that is fixed in the body frame. Compared to a standard hexacopter, this unique design improves the maneuverability of the aerial vehicle, without the price of additional actuators. As opposed to tilting-rotor aerial-vehicle, in the proposed design all actuators generate lift. The paper describes the dynamical model of the novel vehicle and suggests a nonlinear controller to track desired trajectories along five of its DoF. The performances of the design are demonstrated numerically.**

Keywords; multicopter, hexacopter, thrust vectoring, integral backstepping, seesaw, under-actuated system

I. INTRODUCTION

Unmanned Aerial Vehicles (UAVs) are generally under-actuated systems, and it is not possible to control all of their DoF independently. This is because the external forces, used for control, do not span the entire state space [1]. Standard quadcopters are equipped with four propellers, which allows four DoF to be stabilized according to a required task, usually, these are the position and heading. If the angular state is also needed, e.g., for aerial photography, then gimbals with complex structure have to be added to the platform (to tilt the camera to the required orientation). Some other type of multi-copters, such as hexacopters or octocopters use more than four propellers (which improves their survivability and load capacity), but since all generated thrust forces are still parallel, no improvement is achieved with their maneuverability (only four DoF can be controlled independently). A standard multi-copter has to be perfectly level if it is required to hover in a fixed point in space, and if it follows a given trajectory, its two angular states, roll and pitch, have to be determined accordingly. All of this limits the applicability of standard multi-copter platforms, or demands additional onboard equipment which increases the payload.

Nowadays, the multi-copter UAV has become a popular platform for research, due to its simple dynamics, its vertical takeoff and landing (VTOL) capability and its low construction costs [2]. The industrial field is also showing an increasing interest in these UAVs due to their wide range of applications, both, in military and civilian markets. Studies on UAVs concentrate on different aspects, such as control, sensing, communication and cooperation. Improving the UAV structure and flying principle is also a growing researcher field, and efforts are made in order to overcome the under-actuated nature of standard platforms. Different solutions for multi-copters, on the platform level, have been suggested in literature. The tilting rotor structure is an interesting solution which improves both maneuverability and survivability. In this case some or all of the rotors may tilt around a single or dual axis of the platform. The tilting rotor mechanism requires adding more actuators (motors) to the platform. The idea has been suggested in a variety of configurations, such as in [3], [4] for two-rotor UAVs, in [5] for a three-rotor UAV, and in [6] and [7] for quad-rotor UAVs, which led to an over actuated quad-copter that can control all of its six DoF (position and attitude) independently. Tilting wings is a similar idea that tilt the wing and the rotor together ([8]). Another solution (in [9]) is based on a three pairs of perpendicular rotors. This design is featured by six variable-pitch-propellers, arranged in three different rotor planes, in order to point the thrust and torque vectors independently. Consequently, six DoF can be controlled, but the platform is not efficient when in a hovering state, due to the three different rotor planes (which cause opposite force elements that have to cancel each other).

The common drawback of all existing tilting-rotor or tilting-wing UAVs is due to the additional actuators needed for the tilting mechanism; actuators which do not provide lift. In this paper we proposed a novel actuation concept for a hexacopter in which the main body of the UAV can be controlled with five DoF independently, and which can easily be expand to more controlled DoF. The concept does not make use of additional non-supplying lift actuators. In this new structure, four rotors are attached to the main body, while two others are attached to a seesaw. Each rotor generates a force and a torque, as shown in Figure 1. The seesaw is connected to the main body in the center of mass and can rotate freely

978-1-5090-3549-6/16/$31.00 ©2016 IEEE

around one axis of the frame, while the relative angle is measured by a sensor (e.g., a rotary encoder). More importantly it breaks the coupling between the frame orientation and the direction of the generated thrust. In this paper, it is the motion along y and the roll angle ϕ that can be controlled separately.

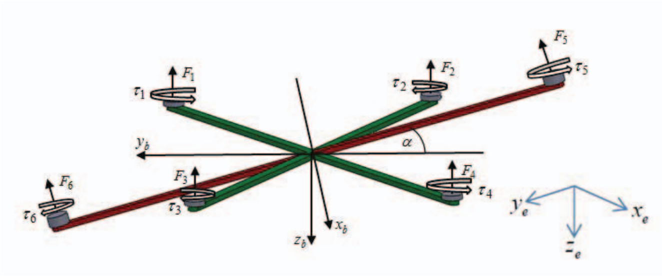


Figure 1. Diagram of forces and torques

The paper presents the dynamical model of the new platform in section II, and the control strategy in section III. Numerical results are shown in section IV, while section V concludes the paper.

II. DYNAMICAL MODEL

Unlike standard hexacopters that can be modeled as a single rigid body, the new hexacopter is composed of two rigid bodies attached in the center of mass by a hinge. This hexacopter state is composed of seven DoF, six to describe the state of the main body (position and attitude) and one for the seesaw angle with respect to the body. In this section, the equations of motion are derived through the Euler-Lagrange principle, with the platform seven DoF as generalized coordinates. Two main coordinate systems are needed for the development of the model, one is attached to the body at the center of mass and represented with the subscript b, and the inertial coordinate system, described with the index e. The relation between the two coordinate systems is expressed by Euler angles and the rotational matrix R, as

$$
{}^{e}R_b = \begin{bmatrix} C\theta C\psi & C\psi S\phi S\theta - C\phi S\psi & C\phi C\psi S\theta + S\phi S\psi \\ C\theta S\psi & C\phi C\psi + S\phi S\theta S\psi & C\phi S\theta S\psi - C\psi S\phi \\ -S\theta & C\theta S\phi & C\phi C\theta \end{bmatrix} \tag{1}
$$

$$C = \cos, \quad S = \sin$$

Another coordinate system (represented with the subscript s) is attached to the seesaw, such that the pitch and yaw angles are identical in the s and b coordinate systems. To express the relation between the angular velocity of the body and the time derivative of Euler angles, the rotational Jacobian J is defined as,

$$
\begin{bmatrix} p \\ q \\ r \end{bmatrix} = J_b \begin{bmatrix} \dot{\phi} \\ \dot{\theta} \\ \dot{\psi} \end{bmatrix}; \quad J_b = \begin{bmatrix} 1 & 0 & -S\theta \\ 0 & C\phi & C\theta S\phi \\ 0 & -S\phi & C\theta C\phi \end{bmatrix}. \tag{2}
$$

The following notation is adopted for the development of the mathematical model. The vector $\xi = [x \quad y \quad z]^T$ represents the position of the center of mass, $\eta = [\phi \quad \theta \quad \psi]^T$ represents the body angular state (i.e., roll, pitch and yaw), α is the relative angle between the seesaw and the body, and β is the angle between the seesaw and the inertial frame. This definition leads to $\beta = \phi + \alpha$. Other symbols are summarized in the following table.

TABLE I. SYMBOLS

symbols	Definition
I_b	Inertia of the body in the body frame
I_s	Inertia of the seesaw in the seesaw frame
m	The vehicle mass
g	Gravity acceleration
σ	$\sigma = [\eta \quad \beta]^T$ (Augmented angle vector)
q	Generalized coordinates
F_ξ	External forces in the inertial frame
τ_σ	External moments
l	Distance between a propeller and the center of mass
$\alpha_{\max}$	The maximum possible angle between the body and the seesaw

The total kinetic energy in (3) is due to the center of mass linear velocity, the main body rotational velocity and the seesaw rotational velocity.

$$
T = \frac{1}{2} m \dot{\xi}^T \dot{\xi} + \frac{1}{2} \dot{\eta}^T D_b(\eta) \dot{\eta} + \frac{1}{2} (\dot{\eta} + \dot{\alpha})^T D_s (\dot{\eta} + \dot{\alpha}) \tag{3}
$$

Here, $D_b(\eta) = J_b^T I_b J_b$ and $D_s(\eta, \alpha) = J_s^T I_s J_s$, and the inertia matrices I_b and I_s are assumed diagonal. Then, the potential energy is expressed by,

$$
U = -mgz \tag{4}
$$

Using (3) and (4), the Lagrangian $L = T - U$ is

$$
L = \frac{1}{2} m \dot{\xi}^T \dot{\xi} + \frac{1}{2} \dot{\eta}^T D_b(\eta) \dot{\eta} + \frac{1}{2} (\dot{\eta} + \dot{\alpha})^T D_s (\dot{\eta} + \dot{\alpha}) + mgz \tag{5}
$$

Now, a four dimensional vector σ is defined, that contains the three Euler angles and the seesaw angle with respect to the world. To simplify (5), the matrices D_b, D_s are expanded and rearranged as R^{4x4} matrices, such that the Lagrangian in (5) can be represented in the following way,

$$
L = \frac{1}{2} m \dot{\xi}^T \dot{\xi} + \frac{1}{2} \dot{\sigma}^T D \dot{\sigma} + mgz \tag{6}
$$

The matrix D contains the expanded and rearranged matrixes D_b, D_s. The equations of motion are derived from L, by,

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}}\right)-\frac{\partial L}{\partial q}=\begin{bmatrix} F_\xi \\ \tau_\sigma \end{bmatrix} \tag{7}$$

Equation (7) can be split into two sets of equations, one for each generalized coordinate vector, ξ (with the three position coordinates) and σ (with the four angular coordinates). The first part of (7) results in,

$$\ddot{\xi}=\begin{bmatrix}0 & 0 & g\end{bmatrix}^T+\frac{1}{m}F_\xi \tag{8}$$

that describes the translational motion. The external force F_ξ is the net force generated by all six propellers and expressed in the inertial frame,

$$F_\xi = \tag{9}$$

$$R\begin{bmatrix} 0 \\ F_5\sin(\alpha)+F_6\sin(\alpha) \\ -(F_1+F_2+F_3+F_4+F_5\cos(\alpha)+F_6\cos(\alpha)) \end{bmatrix}=R\begin{bmatrix} 0 \\ F_s\sin\alpha \\ -F_b-F_s\cos\alpha \end{bmatrix}$$

while $F_i, i=1..6$, are the forces each propeller generates as showed in Fig.1, and the two thrust elements F_b and F_s in (9) are the total thrust generated by the four body propellers and the total thrust generated by the two seesaw propellers, respectively.

Unlike standard hexacopters, where the net thrust has no component in the x or y body directions, in the suggested platform a component along y can be generated. Appling (7) for the augmented angle vector σ, results in the rotational equations of motion, as

$$\ddot{\sigma}=D^{-1}(\sigma)\left[\tau_\sigma+C(\sigma,\dot{\sigma})\dot{\sigma}\right] \tag{10}$$

where $C(\sigma,\dot{\sigma})=\frac{1}{2}\frac{d}{d\sigma}\left[\dot{\sigma}^T D(\sigma)\right]-\dot{D}(\sigma)$.

The external moments $\tau_\sigma=\begin{bmatrix}\tau_\phi & \tau_\theta & \tau_\psi & \tau_\alpha\end{bmatrix}^T$ are the result of the forces and torques generated by the six propellers. The external moments, expressed in the body frame, are

$$\begin{aligned}
&\tau_\phi = l\sin(30)(F_2+F_3-F_1-F_4)+f(\alpha) \\
&f(\alpha)=\begin{Bmatrix} 0, & \alpha<\alpha_{\max} \\ l(F_5-F_6), & \alpha=\alpha_{\max} \end{Bmatrix} \\
&\tau_\theta = l\sin(60)(F_1+F_2-F_3-F_4)+(\tau_5-\tau_6)\sin\alpha \\
&\tau_\psi = \tau_1-\tau_2+\tau_3-\tau_4+(\tau_5-\tau_6)\cos\alpha \\
&\tau_\alpha = l(F_5-F_6), \quad \alpha<\alpha_{\max}
\end{aligned} \tag{11}$$

where τ_i, $i=1..6$, are the pure torques achieved due to rotor spinning, and τ_α is the moment acting on the seesaw due to its two propellers. Throughout this paper it is assumed that $\alpha<\alpha_{\max}$.

Equations (8) and (10) are the equations of motion describing the two rigid bodies. The connection between the seesaw and the main body is in the center of mass of each body, and hence it is the center of mass of the entire vehicle. The bodies are symmetrical, resulting in a diagonal inertia matrix. On the other hand, the gyroscopic moments due to rotor spinning, the friction (between the seesaw and the body) and the (body and seesaw) drag forces have been neglected.

III. Controller Design

This section describes the development of the control system. The control law controls five of the body DoF independently, allowing the vehicle to follow a spatial trajectory with prescribed roll and yaw angles.

There are two parts in the control system, the first is a high bandwidth controller that stabilizes the angular state (attitude and seesaw), it is the attitude controller. The second is a low bandwidth position controller, with two elements. The first element generates the required thrust in order to stabilize the altitude ($z_d(t)$, according to a desired spatial trajectory). The second element is in charge of the navigation task. It translates desired position ($x_d(t), y_d(t)$, of the reference spatial trajectory) into desired pitch and seesaw angles (which are then fed into the angular controller as reference signals). The block diagram in Fig. 2 shows the layout of this controller.

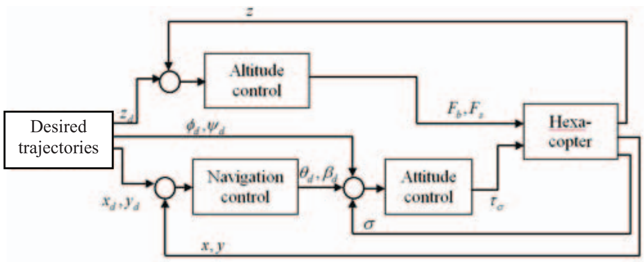


Figure 2. Controller layout

A. *Attitude Control*

The attitude controller is presented first; it is based on the integral back-stepping approach ([2]) and acts on the complete angle vector σ. The error between the desired attitude σ_d and the actual attitude σ, and the time derivative of the error, are

$$e_\sigma=\sigma_d-\sigma; \quad \dot{e}_\sigma=\dot{\sigma}_d-\dot{\sigma} \tag{12}$$

The desired dynamics for the attitude would be achieved if,

$$\dot{\sigma}=\dot{\sigma}_w \triangleq c_1 e_\sigma+\dot{\sigma}_d+k_\sigma\chi_\sigma \tag{13}$$

where c_1, k_σ are diagonal positive definite matrices with control gains, and χ_σ represents the integration of the error e_σ (with respect to time). Since $\dot{\sigma}$ it not a physical input, an error signal is defined with respect to $\dot{\sigma}_w$ as,

$$e_{\sigma'} = \dot{\sigma}_w - \dot{\sigma} \tag{14}$$

and its time derivative is,

$$\frac{de_{\sigma'}}{dt} = \dot{e}_{\sigma'} = \ddot{\sigma}_w - \ddot{\sigma} = c_1\dot{e}_\sigma + \ddot{\sigma}_d + k_\sigma e_\sigma - \ddot{\sigma} \tag{15}$$

In order to express (15) as a function of the errors ($e_\sigma, e_{\sigma'}$), (13) and (14) are used in (12). Then, the result is substituted in (15), which gives,

$$\dot{e}_{\sigma'} = c_1(-c_1 e_\sigma - k_\sigma \chi_\sigma + e_{\sigma'}) + \ddot{\sigma}_d + k_\sigma e_\sigma - \ddot{\sigma} \tag{16}$$

The designed controller will shape the dynamics of this error to be,

$$\dot{e}_{\sigma'} = -c_2 e_{\sigma'} - e_\sigma \tag{17}$$

where c_2 is a diagonal positive define matrix. By substituting (13), (14) and (17) in (16), one has,

$$\begin{aligned} &\ddot{\sigma} = \ddot{\sigma}_d + k_P e_\sigma + k_D \dot{e}_\sigma + k_I \chi_\sigma \\ &k_P = I_{4x4} + k_\sigma + c_1 c_2 \\ &k_D = c_1 + c_2 \\ &k_I = c_2 k_\sigma \end{aligned} \tag{18}$$

which represents the required angular acceleration, that is now expected to be translated to body moments (i.e., the physical inputs). In order to find the moments that will cause the error tend to zero, (18) is used in (10), which results in,

$$\tau_\sigma = D(\sigma)\{\ddot{\sigma}_d + k_P e_\sigma + k_D \dot{e}_\sigma + k_I \chi_\sigma\} - C(\sigma, \dot{\sigma})\dot{\sigma} \tag{19}$$

B. *Position control*

This controller is responsible for the translational motion in space. It receives the desired trajectory ($x_d(t)$, $y_d(t)$ and $z_d(t)$) as a reference signal and generate the required thrust, pitch and seesaw angles. Its altitude control element is presented first.

Using the same procedure as presented for the attitude controller (based on the integral back-stepping technique) and with (9|), one has,

$$F_b = \frac{m\left(g - k_{Pz}e_z - k_{Dz}\dot{e}_z - k_{Iz}\chi_z - \ddot{z}_d\right) - F_s\cos\theta\cos\beta}{\cos\theta\cos\phi} \tag{20}$$

where the control gains $k_{Pz} = 1 + k_z + c_{z1}c_{z2}$, $k_{Dz} = c_{z1} + c_{z2}$, $k_{Iz} = c_{z2}k_z$ and c_{1z}, c_{2z}, k_z are positive and constant scalars. Basically, the altitude may be controlled by two possible control signals F_b or F_s. In the current development, only the four body propellers are used for altitude control, while F_s will be determined later.

The second element of the position controller determines the seesaw and pitch angles. These desired angles are then fed into the attitude controller as reference signals. The pitch angle is in charge of the movement along x (in the body frame) and the seesaw angle is required for the motion in the direction of y. The controller which determines a desired seesaw angle is presented now. The control strategy is identical to the one used for the development of the attitude controller. Appling the back-stepping approach, the required acceleration along y is,

$$\begin{aligned} &\ddot{y} = \ddot{y}_d + k_{Py}e_y + k_{Dy}\dot{e}_y + k_{Iy}\chi_y \\ &k_{Py} = 1 + k_y + c_{y1}c_{y2}, \quad k_{Dy} = c_{y1} + c_{y2}, \quad k_{Iy} = c_{y2}k_y \end{aligned} \tag{21}$$

and with (9), the desired seesaw angle is,

$$\beta_d = \sin^{-1}\left(\frac{m(\ddot{y}_d + k_{Py}e_y + k_{Dy}\dot{e}_y + k_{Iy}\chi_y) - F_b\sin\phi}{F_s}\right) \tag{22}$$

This result is based on the assumption that the yaw angle is zero, which does not limit the generality of the controller, but simplifies the development. If the yaw angle isn't null, one may rotate the inertial frame with the actual yaw angle to apply the presented controller. The net seesaw force F_s in (22) is still an independent variable that may now be utilized to fulfill an additional constraint. One option is to define F_s as,

$$F_s = p_1 e_{\Delta y} + p_2 \tag{23}$$

where $e_{\Delta y} = m\left(\ddot{y}_d + k_{Py}e_y + k_{Dy}\dot{e}_y + k_{Iy}\chi_y\right) - F_b\sin\phi$ while $P_1 \geq 1$ and $P_2 > 0$ are constants. With this choice (and (22)), one has,

$$\sin\beta_d = \frac{e_{\Delta y}}{p_1 e_{\Delta y} + p_2} \tag{24}$$

This assures that $\sin\beta_d < 1/p_1$ (for any $e_{\Delta y}$). Thus, p_1 can be defined with the max angle allowed for the seesaw. A reasonable choice for P_2 would be $P_2 = 2mg/6$, since for $e_{\Delta y} = 0$ (and from (23)) one has $F_s = p_2$; this way the load is fairly shared between the body and the seesaw propellers.

Using the same control approach, the required acceleration along x is,

$$\begin{aligned} &\ddot{x} = \ddot{x}_d + k_{Px}e_x + k_{Dx}\dot{e}_x + k_{Ix}\chi_x \\ &k_{Px} = 1 + k_x + c_{x1}c_{x2}, \quad k_{Dx} = c_{x1} + c_{x2}, \quad k_{Ix} = c_{x2}k_x \end{aligned} \tag{25}$$

and with (9), the reference pitch angle is,

$$\theta_d = \sin^{-1}\left(\frac{m(\ddot{x}_d + k_{Px}e_x + k_{Dx}\dot{e}_x + k_{Ix}\chi_x)}{-F_s\cos\beta - F_b\cos\phi}\right) \tag{26}$$

IV. NUMERICAL RESULTS

To validate the controller suggested in section III, and to demonstrate the ability of the new platform to track a desired trajectory with five DoF controlled independently, MATLAB numerical simulations are presented in this section.

In the presented scenario, the initial conditions are defined as,

$$\begin{aligned} &\phi_0 = \theta_0 = \psi_0 = \beta_0 = 0\,[rad] \\ &x_0 = y_0 = 0\,[m] \\ &z_0 = -1\,[m] \end{aligned} \tag{26}$$

and the desired trajectory is,

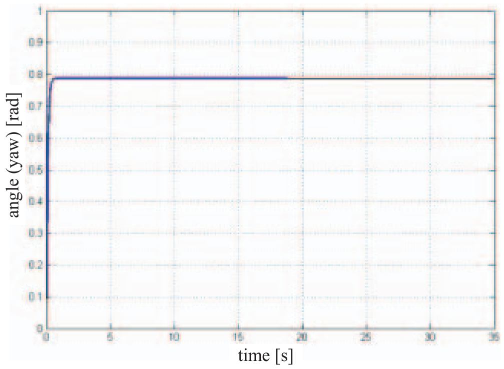
$$\begin{aligned} &\psi_d = \pi/4\,[rad] \\ &\phi_d = 0.1\sin(t/2)\,[rad] \\ &x_d = -1[m] \\ &y_d = 2\sin(t)[m] \\ &z_d = -t/5 \end{aligned} \tag{27}$$

The hexacopter actual trajectories and the desired trajectories are presented in Fig. 3, which includes all five controlled DoF. It can be seen that this new hexacopter follows all required coordinates, and the zero yaw angle assumption made in the development of the navigation controller puts no limitations.

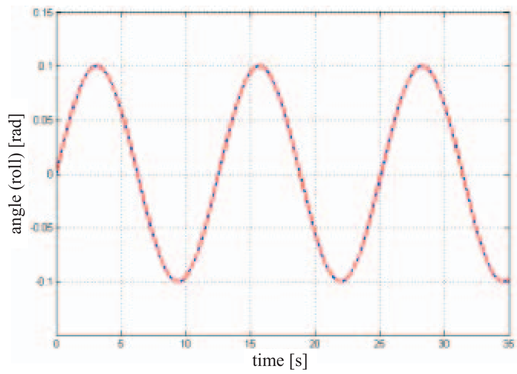
Fig. 4 shows the pitch and the seesaw angles needed in order to track the desired trajectories. The seesaw angle is utilized here for the required tracking task, and it is influenced by the pitch angle, as can be seen in (22). Fig. 5 shows the net-force of the four body propellers and the net-force of the two seesaw propellers. The body net-force controls the altitude and the seesaw net-force is calculated according to (23), with $P_1 = 1$ and $P_2 = 9.81/3$.

V. CONCLUSION

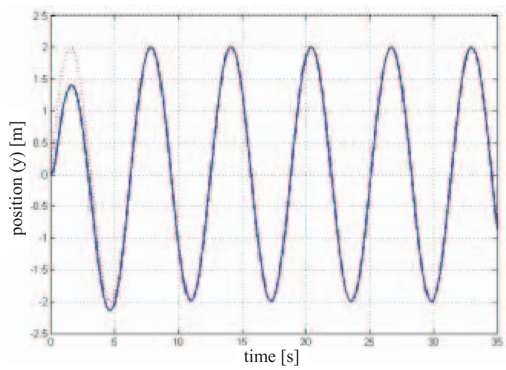
In this paper, the under-actuation problem of standard multi-copters has been addressed. The proposed solution is based on a novel structure of a hexacopter platform with a seesaw. The seesaw is free to rotate about one of the body frame axes. The new platform improves the aerial vehicle maneuverability and allows controlling five of its DoF independently. The dynamical model has been developed, without any assumption of small angles. Based on the dynamical model, a non-linear trajectory tracking controller has been developed that uses the principles of integral back-stepping control. The control system and the conceptual platform have been demonstrated numerically. The simulated scenario has demonstrated a trajectory tracking task of five independent DoF. Future research will consider development of platforms with more than a single seesaw and flight tests to demonstrate the feasibility of the concept



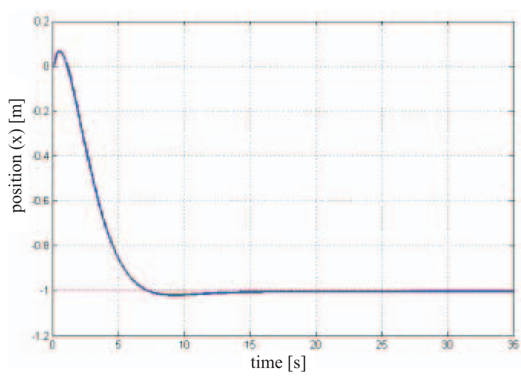
(a)



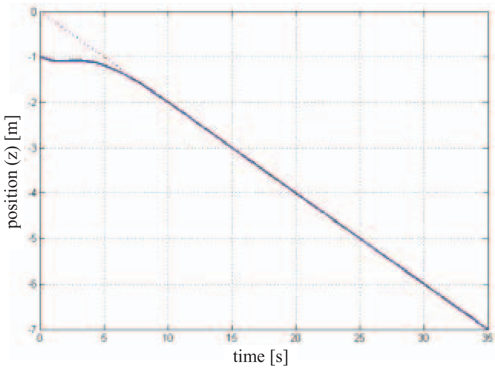
(b)



(b)

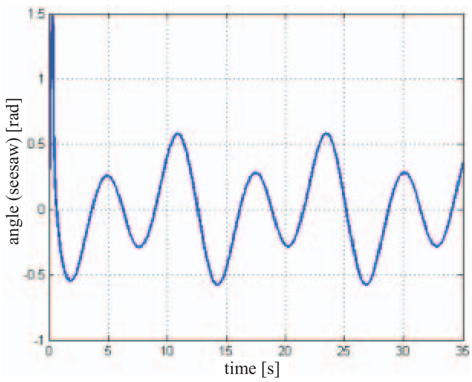


(d)

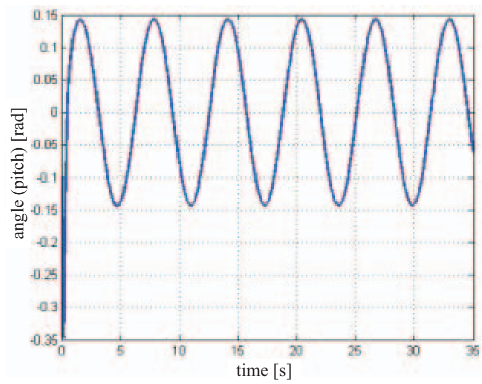


(e)

Figure 3. Simulation results of five DoF trajectory tracking controller, blue solid line represents an actual trajectory and the red dotted line a desire trajectory. The shown coordinates are: (a) yaw angle, (b) roll angle, (c) position along y, (d) position along x and (e) position along z.

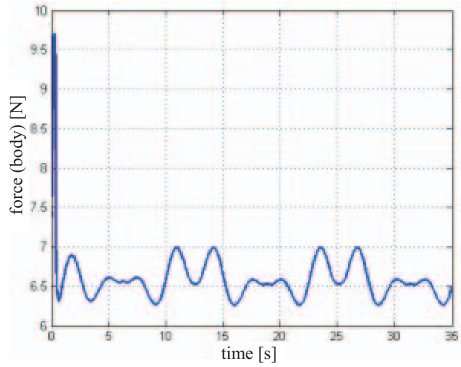


(a)

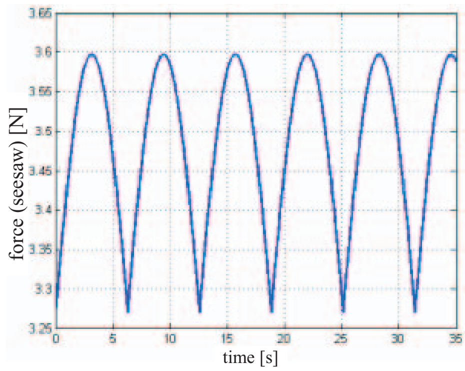


(b)

Figure 4. The angles: (a) of the seesaw, (b) the pitch, that are required for the trajectory tracking task.



(a)



(b)

Figure 5. Net forces, generated by: (a) the body propellers, (b) the seesaw propellers.

REFERENCES

[1] P. Xavier and M. La Hera, "Underactuated Mechanical Systems: Contributions to trajectory planning, analysis, and control". PhD dissertation, Umeå University, 2011.

[2] S. Bouabdallah, “Design and control of quadrotors with application to autonomous flying,” PhD dissertation, Lausanne, EPFL, 2007.

[3] A. Sanchez, J. Escare˜no, O. Garcia, and R. Lozano,“Autonomous hovering of a noncyclic tiltrotor UAV: Modeling, control and implementation,” in Proc. of the 17th IFAC Wold Congress, 2008, pp. 803–808.

[4] F. Kendoul, I. Fantoni, and R. Lozano, “Modeling and control of a small autonomous aircraft having two tilting rotors,” IEEE Trans. on Robotics, vol. 22, no. 6, pp. 1297–1302, 2006.

[5] J. Escareno, A. Sanchez, O. Garcia, and R. Lozano "Triple Tilting Rotor mini-UAV: Modeling and Embedded Control of the Attitude", in 2008 American Control Conference, 2008.

[6] M. Ryll, H. H. Bulthoff, and P. Robuffo Giordano, “Modeling and Control of a Quadrotor UAV with Tilting Propellers,” in 2012 IEEE Int. Conf. on Robotics and Automation, 2012.

[7] A. Nemati and M. Kumar, "Modeling and Control of a Single Axis Tilting Quadcopter" in 2014 American Control Conference, 2014.

[8] K. T. Oner, E. Cetinsoy, M. Unel, M. F. Aksit, I. Kandemir, and K. Gulez, “Dynamic model and control of a new quadrotor unmanned aerial vehicle with tilt-wing mechanism,” in Proc. of the 2008 World Academy of Science, Engineering and Technology, 2008, pp. 58-63.

[9] D. Langkamp, G. Roberts, A. Scillitoe, I. Lunnon A. Llopis-Pascual, J. Zamecnik, S. Proctor, M. Rodriguez-Frias, M. Turner, A. Lanzon and W. Crowther. "An engineering development of novel hexrotor vehicle for 3D applications", in Proceedings of the International Micro Air Vehicles conference summer edition, 2011, pp. 32-39.