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An Image Based Visual Servoing Approach for Multi-Target Tracking Using an Quad-Tilt Rotor UAV

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***Abstract*—This paper proposes a guidance algorithm of a UAV for multiple targets tracking, considering physical constraints of the platform and its sensor. The on-board sensor used for target tracking is a camera. To relax the need of a gimbal system and provide flexibility in utilisation of the vision sensor, a new rotorcraft type of UAV is developed. The main focus in designing tracking guidance is to develop an image based visual servoing approach, appropriate to the newly developed platform. A complementary to the guidance system a control system for the unconventional UAV is also presented. Both control and guidance algorithms are based on the PID control techniques and this paper shows that the tracking guidance can be significantly simplified with the new type of UAV developed. The performance of the proposed tracking guidance along with the controller designed is validated by numerical simulations and flight tests.**

I. Introduction

The large scale of UAV applications has proliferated vastly within the last few years. The operational experience of UAVs has proven that their technology can bring a dramatic impact to military and civilian arenas. This includes, but not being limited to: obtaining real-time, relevant situational awareness; helping commanders to lead appropriate decision making; and reducing risk to the mission and operation. One key feature enabling aforementioned advantages is that UAVs are sensing platforms.

As a sensing platform, one of most relevant UAV operations would be target tracking. To this end, there have been extensive studies on target tracking. This paper also addresses the target tracking problem, including multi-target tracking, using a quad-rotor type of UAV. Note that such a UAV type has been drawing increasing attention due to its simplicity in control, as well as vertical take-off and hovering capabilities. These capabilities are greatly beneficial in target tracking.

Many existing literature in target tracking have tackled with the tracking problem of a single target [1], [2], [3], [4], [**?**] [5], [6], [7], [8], [9], [10]. Majority of the algorithms developed on those studies are based on Image Based Visual Servoing (IBVS) or Position Based Visual Servoing (PBVS) methods. The introduction to classical Visual Servoing can be found in [11], [12], [13]. General disadvantages and analysis of IBVS are presented in [14], [6] . More advanced IBVS forms can be found, e.g. in [8]. Note that, in general, those papers assumed a stationary target.

A wide range of different control types are utilised for target tracking. Most of them used a simple P or PD controllers to keep the target in a desired position in the image plane. On the other hand, [15] and [16] introduced a concept of a so called Visual Predictive Control, a method for target tracking based on Model Predictive Control. In both [4] and [**?**] a backstepping algorithm was proposed to control the UAV. Additionally, in [**?**] an adaptive scheme is proposed in order to compensate for the unknown parameters. [17], [18], [19] presented other approaches to adaptive control and estimation of distance (depth) to the target, which is an important parameter in target tracking missions.

[4] and [**?**] also described the problem of underactuation of a standard Quadrotor UAV and its influence on target tracking. In standard Quadrotor only four out of its six degrees of freedom can be controlled independently. Usually three Euler angles and altitude are controlled. In such a case, in order to control the lateral or longitudinal velocity of the UAV, an attitude of the UAV must be changed. As a result of the attitude change, the objects also change its position in the image frame. As a resolution, [4] and [**?**] suggested to project the targets position in the image on a virtual plane, taking the roll and pitch angles of the Quadrotor into account. Some other ways of dealing with the underactuation problem were also discussed in [3] and [5].

There have been also some studies on multi-target tracking [20], [21], [22], [23]. The majority of those studies presented the theoretical, kinematic investigation of the approach. Only paper [23] applies the guidance to a mobile ground robot and takes the constraint of the platform into account. In [23], a PID controller is implemented to control the linear and angular velocity of the robot. The main goal of this controller was to control mean position and standard deviation of the objects in the image plane: the target mean is chosen to be the image centre and the variance of image points is chosen small enough to prevent object to leave the field of view of the camera.

In [20], [21], [22], a theoretical investigation of their guidance algorithms was presented. In order to keep multiple objects in the camera's FOV, mean and variance are controlled with output velocity profile. In those papers, control of one parameter (e.g. mean or variance) is called a task function. Proposed approach for guidance is to prioritize different task functions. If the velocity commands for different task functions are contradictory, velocity command of function with higher priority is chosen. The method used for obtaining a velocity command in such a way is called a task-priority kinematic control.

In the aforementioned three papers, it is assumed that all the 6 degrees of freedom of the camera can be controlled independently and no movement constraints on a mobile platform are considered. The issue is that these assumptions neither realistic, nor practical.

This paper first focuses on developing a solution to the multi-target tracking problem, especially in consideration of physical and operational constraints of the platform and its on-board sensors. The on-board sensor considered for the tracking is a vision sensor, i.e. a camera. Instead of utilising a gimbal system to control the vision sensor, we developed a new type of quad-rotor UAV, called Quad-Tilt UAV. This new type of platform has one additional mechanism, forward tilting of the rotors, and thus provides one more degree of freedom to the system. The forward movement can be obtained by controlling tilting angle of the rotors. Consequently, the lateral motion of the platform can be fully controlled without changing attitude of the UAV. This allows us to omit the gimbal system from the platform and hence provides great flexibility in utilising vision sensors.

The second focus of this paper is to develop a tracking guidance algorithm, appropriate to the new platform developed. As a vision sensor, i.e. camera, is utilised, the proposed tracking guidance algorithm is based on the IBVS approach. This paper shows that the guidance algorithm can be simplified with the platform we developed. The main consideration in the our tracking guidance design is to update the classical IBVS approach to match the dynamics of the new Quad-Tilt Rotor UAV. The proposed guidance algorithm is based on the classical PID techniques and controls the mean of positions of the multiple targets and their mean distance from the mean position. The outputs of the proposed guidance algorithm consist of forward and vertical linear velocities and yaw rate. The performance of the proposed tracking guidance algorithms and the new type of UAV is validated through both numerical simulations and flight tests.

II. UAV System Design

A manufactured prototype of a Quad-Tilt Rotor UAV is shown in Fig. 1.

Fig. 1. Manufactured Prototype of a QTR used for flight tests

This UAV was manufactured to test its possible performance during targets tracking without using an usually heavy and costly gimbal platform. In order to succeed in a target tracking mission, it is necessary to point the camera into the direction of the targets at all times during the mission.

The classical quadcopter platform, that has its motors fixed to the frame, is an underactuated system. It has smaller amount of inputs (4) than degrees-of-freedom (6). Thus, in order to move in a horizontal plane it is required to change attitude of the Quadcopter. During the change of attitude, the camera frame changes its orientation with respect to the tracked objects. This effect should be taken into account in guidance algorithm design, which lead to higher complexity of the algorithm.

Adding additional control input to a Quad-Tilt Rotor UAV system allows for controlling 5 degrees-of-freedom (DOF) independently. Possible virtual inputs to the UAV are given by equation (1).

$$\mathbf{u} = \begin{bmatrix} L & M & N & X & Z \end{bmatrix}^T \tag{1}$$

Where:
L - rolling moment
M - pitching moment
N - yawing moment
Z - thrust component in Z-body axis
X - thrust component in X-body axis

The actuation rolling, pitching and yawing moments of the UAV are obtained with the differential thrust of the four UAV motors. The vertical component of the thrust Z is generated due to overall thrust of the motors. The additional component of force in X-body axis is obtained due to the tilting of the UAV rotors. Using such platform allows for independent control of pitch attitude and forward velocity. Thus, aircraft can fly forwards and backwards keeping the pitch attitude constant and keeping the camera pointed towards the targets. Movement in lateral axis of the quadcopter still remains underactuated, i.e. movement in lateral direction of the UAV requires to change the attitude of the UAV. Because of that reason, it is avoided to use lateral velocity in guidance.

III. Guidance System Design

The guidance and control laws described in this paper are designed in a form of a hierarchical system presented in the Fig. 2. Based on the error between the visual data provided by the camera and the reference value, the guidance law output a reference profile of velocity and attitude for a control system. Control system drives the throttle and motors tilting to obtain the reference values provided by the guidance law.

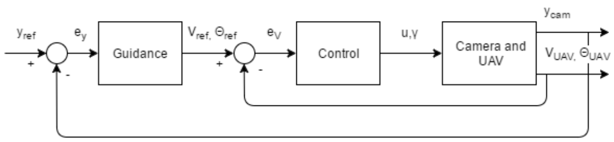

Fig. 2. Block diagram of a guidance and control systems used in this paper

The suggested guidance law requires a velocity estimation to be available for feedback. One of the methods to estimate the linear velocity of the UAV is to use a sensor fusion algorithm to fuse the data from GPS and IMU. This approach limits the operational range only to places where GPS signal is available. Another possibility is to use the visual data to estimate relative velocity between an object and a UAV.

A. Multiple Objects Tracking

Proposed guidance algorithm is designed and tested, based on the following assumptions about targets movement:
Assumption 1: Algorithm should be capable of tracking of at least three targets.
Assumption 2: Initially, all the targets are within the FOV of the camera.
Assumption 3: Objects are moving independently from each other. Their movement is modelled with adding a random acceleration of a bounded value.
Assumption 4: Loss of visibility of targets due to occlusion is not taken into account.

The algorithm proposed in this paper focuses on maintaining targets in the camera FOV. It does not take the resolution of the targets into account. This can result in a low resolution of targets. The solution to this problem however is addressed for the future work.

In case of single object tracing, in order to ensure that an object is maintained in the camera FOV, it is maintained at a reference position in the centre of the image frame. In case of independently moving multiple objects it is not possible to guide UAV in such a way to ensure that each of the targets occupies a reference position in the image. In this paper a mean position of targets is controlled. Its reference is the image centre. The reference mean parameter is give by equation (2).

$$\begin{bmatrix} x_m \\ y_m \end{bmatrix} = \frac{1}{k} \sum_{i=1}^{k} \begin{bmatrix} x_i \\ y_i \end{bmatrix} \tag{2}$$

Where:
- k is number of targets currently in the field of view in the camera
- x_i, y_i - are horizontal and vertical coordinates of position of the i-th target in the image frame.

Keeping the mean of the targets in the image centre decreases the probability of targets leaving the field of view of the camera. Nevertheless, it might happen that the mean of targets' position is in the middle of the image frame but the targets are located at its edges. To secure the guidance from such condition, tracked targets should be kept relatively close to the image centre. In papers [20], [22], [21], variance of position of the targets in the image is used to keep objects away from its edges. In this paper a mean distance of the targets from the mean is used instead. Such approach was adopted because this parameter is equal in all the directions while, variance of targets position can be in general different in horizontal and vertical directions. Virtual parameter of mean distance of targets form the mean position of targets is given by equation 3.

$$m_d = \frac{1}{k} \sum_{i=1}^{k} |m_m - m_i| = \frac{1}{k} \sum_{i=1}^{k} \sqrt{(x_m - x_i)^2 + (y_m - y_i)^2} \tag{3}$$

Where:
- m_d is mean distance of targets in the image from the actual mean position of targets
- m_m is mean position of the targets in camera frame

From the above discussion it is concluded that proper control of the following three parameters:

- the mean position of targets in the image in x and y axes, defined by equation (2)
- the distance of targets from the mean (spread of targets) in the image, defined by equation (3)

should allow for maintaining the targets in the image frame.

B. Image Based Visual Servoing

In order to keep the targets in the desired positions in the image frame it is required to know what is the dependency between UAV (camera) movement and the resulting targets movement in the image.

Consider a point $P_c = [X_c, Y_c, Z_c]$ in a 3D frame attached to the camera. Using a pinhole camera model and a perspective projection equation (see Fig. 3), point P_c projected on the 2D image plane has the following coordinates:

$$\begin{aligned} x &= f \cdot \frac{X_c}{Z_c} \\ y &= f \cdot \frac{Y_c}{Z_c} \end{aligned} \tag{4}$$

Where:
- x, y - horizontal and vertical coordinates of a point in image plane expressed in pixel units
- f - camera focal length expressed in pixel units

Taking the time derivative of the equation (4) and expressing the velocity vector in the earth coordinate system, the equation

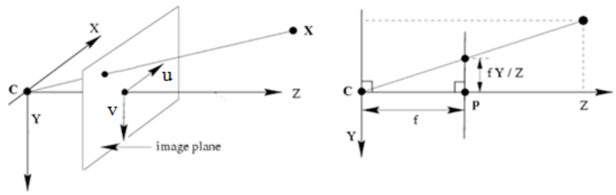

Fig. 3. Pinhole Camera model - projective projection

(5) is derived. Full derivation of equation (5) can be found in [8], [11] or [12].

$$\begin{bmatrix} \dot{x} \\ \dot{y} \end{bmatrix} = \begin{bmatrix} -\frac{f}{Z} & 0 & \frac{x}{Z} & \frac{xy}{f} & \frac{-f^2-x^2}{f} & y \\ 0 & -\frac{f}{Z} & \frac{y}{Z} & \frac{f^2+y^2}{f} & -\frac{xy}{f} & -x \end{bmatrix} \begin{bmatrix} v_{x,c} \\ v_{y,c} \\ v_{z,c} \\ \omega_{x,c} \\ \omega_{y,c} \\ \omega_{z,c} \end{bmatrix} \quad (5)$$

The vector that contains linear and angular velocities in equation (5) is called a velocity screw vector. Its components in equation (5) are expressed in the camera frame (c-subscript). Equation (5) represent the dependency between the camera (UAV) movement and the rate of change of the object position in the image frame (provided that the object is static). An Image Jacobian (also known as Interaction Matrix) can be distinguished from the equation (5). It is usually denoted with L and is presented in equation (6).

$$L = \begin{bmatrix} -\frac{f}{Z} & 0 & \frac{x}{Z} & \frac{xy}{f} & \frac{-f^2-x^2}{f} & y \\ 0 & -\frac{f}{Z} & \frac{y}{Z} & \frac{f^2+y^2}{f} & -\frac{xy}{f} & -x \end{bmatrix} \quad (6)$$

Matrix L contains:
- Z - depth to the object. That is the distance between the image plane and the tracked target.

However, while using a monocular camera an information about the depth to the object is lost. In this paper, the depth to the target is assumed to be known.

The basic idea of he IBVS is to observe the difference between actual position of the targets in the image to the desired, reference position. Based on the error a velocity screw command is computed (see Fig. 2). An error between desired and actual position of some image feature is give by the equation (7).

$$e = m - m_{ref} \quad (7)$$

Where:
m_{ref} - desired position of the tracked feature in the image plane
m - actual position of the tracked feature in the image plane
$e(t)$ - error between desired and actual positions in the image plane.

Taking the derivative of equation (7) and provided that the reference position m_{ref} is constant, the following equality is obtained:

$$\dot{e} = \dot{m} \quad (8)$$

Substituting (8) to (5), the equation describing rate of change of the error is obtained:

$$\dot{e} = L \cdot V_{cam} \quad (9)$$

Where:
L - the Jacobian matrix defined in equation (5)
V_{cam} - camera velocity screw

In order to ensure exponential decrease of the error the derivative of the error should have the form:

$$\dot{e} = -K_p \cdot e \quad (10)$$

Where K_p is a positive scalar constant. Combining equations (10) and (9) leads to the equation:

$$-K_p \cdot e = L \cdot V_{cam} \quad (11)$$

Multiplying both sides of the equation by the inverse of the image Jacobian, results in the expression for the velocity screw command given in equation (12).

$$V_{cam} = -K_p \cdot L^{-1} \cdot e \quad (12)$$

Knowing the Jacobian matrix L and having defined the desired position of the image feature in the image, equation (12) can be used to calculate velocity profile. The proportional gain K_p defines the speed of error decay and is a design parameter. A similar derivation to the one presented can be found in [11].

The inverse of the Jacobian matrix is only possible when matrix L is full 6x6 matrix. Typically the Moore-Penrose pseudoinverse of the matrix L is used instead [11].

The equation (13) was derived with an assumption that target was static. In such a case the change in position of the target in the image frame is only due to the controlled motion of the camera (UAV). When the target moves, the velocity command has a general form [11]:

$$V_{cam} = -K_p \cdot L^{-1} \cdot e - L^{-1}\frac{\partial e}{\partial t} \quad (13)$$

Where:
$\frac{\partial e}{\partial t}$ - a change of an error due to targets' motion.

In this paper, targets movement is treated as an external disturbance to the system. In order to account for this disturbance, an integral action is added to the guidance law. If the UAV moves fast enough compared to the objects' movement this approach should give satisfactory results. Another approach to compensate the law for targets movement could be to use an observer and estimate objects velocity. Also a relative velocity between object and the UAV can be obtained with a use of an optical flow sensor.

Equation (5) shows that in general all the velocity components have an impact on the rate of change of the image features. If the Jacobian matrix in equation (12) has 6 columns, the full 6x1 velocity screw vector is output. However, taking the dynamics of the UAV into account, the velocity reference vector V_{ref} might be simplified. Analysis of equation (5) leads to a conclusion which velocity components are the most significant to the rate of change of the targets' position in the image frame.

C. Mean position of targets

The reference point for the mean position of the targets is the image centre. Its coordinates are: $x_{ref} = 0$ and $y_{ref} = 0$. If the mean position of targets is maintained in the vicinity of the reference point then all the components of Image Jacobian (6) that contain x or y in the numerator are close to zero and can be neglected. Following the presented consideration, the Image Jacobian Matrix is decoupled, simplified and presented in equation (14).

$$\begin{aligned} \dot{x} &= \begin{bmatrix} -\frac{f}{Z} & \frac{-f^2-x^2}{f} \end{bmatrix} \begin{bmatrix} v_{x,c} \\ \omega_{y,c} \end{bmatrix} \\ \dot{y} &= \begin{bmatrix} -\frac{f}{Z} & \frac{f^2+y^2}{f} \end{bmatrix} \begin{bmatrix} v_{y,c} \\ \omega_{x,c} \end{bmatrix} \end{aligned} \tag{14}$$

From the above discussion, it can be concluded that:

- Yaw rate and lateral velocity have the biggest impact on rate of change of target position in the image in horizontal axis. Pitch rate, roll rate, forward and vertical velocity have negligible impact on horizontal position of targets.
- Pitch rate and vertical velocity have the biggest impact on rate of change of target position in the image in vertical axis. Yaw rate, roll rate, forward and lateral velocity have negligible impact on vertical position of targets.

During further considerations, taking the dynamics of the designed UAV into account the image Jacobian matrix can be further simplified. The control of lateral velocity would require aircraft to change its attitude. Thus, the position of the targets on the image frame would be changed. There are some methods presented e.g. in [4], [**?**] that propose a solution to this problem but they increase the complexity of the algorithm.

Finally, because of the UAV dynamics, only yaw rate is used to control the horizontal position of the mean position of objects in the image frame. Also, because of the simplicity of the design of the control system, only vertical velocity of the UAV is used to control change of position of the targets in the vertical axis. The pitch attitude angle reference is always set to zero. Such approach is possible because of the dynamics of the UAV used in this paper.

The image Jacobian matrix is then simplified to its final state presented in equation (15).

$$\begin{aligned} \dot{x} &= \frac{-f^2-x^2}{f}\omega_{y,c} \\ \dot{y} &= -\frac{f}{Z}v_{y,c} \end{aligned} \tag{15}$$

Linear forward velocity is used to control the spread of targets in the image.

Equation (15) contains the depth to targets Z. In this paper the mean depth to all the targets is used. Mean depth is given by equation (16).

$$Z = \frac{1}{k}\sum_{i=1}^{k} Z_i \tag{16}$$

D. Guidance Law

The final form of guidance law is based on the combination on equation (12) and a simplified version of an Image Jacobian given in equation (15).Additionally I and D terms are added to the standard IBVS law. Each of the gains has a different function:

- K_p - is the main source of reducing guidance error to zero.
- K_i - has to compensate for unknown target movement.
- K_d - has to decrease the overshoot of the response. Too big overshoot could result in lose of the target from the FOV.

In general, a reference velocity screw vector has six components. According to the kinematic investigation of the Image Jacobian and the constraints of the UAV platform, some of its components are always referenced to zero.

$$\mathbf{V_{ref}} = \begin{bmatrix} V_{x,b} & 0 & V_{z,b} & 0 & 0 & \omega_{z,b} \end{bmatrix}^T \tag{17}$$

Subscript b in equation (17) denotes quantities expressed in body reference coordinate system. Dependency between the reference systems is presented in equation (18).

$$\begin{aligned} X_b &\equiv Z_c \\ Y_b &\equiv X_c \\ Z_b &\equiv Y_c \end{aligned} \tag{18}$$

The way of computing ω_z, V_x and V_z are presented in (19), (20), (21).

$$\begin{aligned} e_{\mu_x} &= x_{ref} - x = -x \\ \omega_{z_{ref}} &= -\frac{f}{-f^2-x^2}(K_p e_{\mu_x} + K_i \int e_{\mu_x} dt + K_d \frac{e_{\mu_x}}{dt}) \end{aligned} \tag{19}$$

$$\begin{aligned} e_{\mu_y} &= y_{ref} - y = -y \\ V_{z_{ref}} &= -\frac{Z}{f}(K_p \cdot e_{\mu_y} + K_i \int e_{\mu_y} dt + K_d \frac{e_{\mu_y}}{dt}) \end{aligned} \tag{20}$$

$$\begin{aligned} e_{m_d} &= m_{d_{ref}} - m_d \\ V_{x_{ref}} &= K_p \cdot e_{m_d} + K_i \cdot \int e_{m_d} \cdot dt \end{aligned} \tag{21}$$

IV. Control System Design

Control system is designed to be complementary with the Guidance system. The control state vector is presented in equation (22).

$$x_{control} = \begin{bmatrix} V_x & V_z & \phi & \theta & \dot{\psi} \end{bmatrix}^T \tag{22}$$

Where:
V_x - forward velocity expressed in body coordinate system
V_z - vertical velocity expressed in body coordinate system
ϕ - roll attitude angle
θ - pitch attitude angle
$\dot{\psi}$ - yaw rate expressed in body axis

For a design of a controller, quadcopter dynamics are considered as a set of Single Input Single Output (SISO) systems. The tilting rotors effect is considered as a form of external disturbance to the UAV dynamics control loop. Instead of controlling the lateral velocity, the roll angle is controlled and its reference is set to zero.

A. Linear Velocity Control

Forward velocity of the UAV is controlled with tilting angle of rotors. Reference tilt angle γ_{ref} is computed based on the control law presented in equation (23).

$$\begin{aligned} e_{V_x} &= V_{x_{ref}} - V_x \\ \gamma_{ref} &= K_p \cdot e_{V_x} + K_d \cdot \frac{e_{V_x}}{dt} \end{aligned} \tag{23}$$

During the simulation result analysis, it was noticed that the fast changes of the tilting mechanism resulted in significant influence on the pitch attitude. To slow down the tilting process the reference forward velocity profile is filtered with a low pass filter.

Vertical velocity control law is given by equation (24). The controller operates around the trim point state Z_0 which is a throttle level required for hover.

$$\begin{aligned} e_{V_z} &= V_{z_{ref}} - V_z \\ Z &= Z_0 + K_p \cdot e_{V_z} + K_i \cdot \int e_{V_z} \cdot dt \end{aligned} \tag{24}$$

B. Attitude Control

In order to control pitch and roll attitude angles of the UAV a 2 degrees-of-freedom PID controller is used. Such form of the controller is more reliable and ensures high control bandwidth.

Rotors tilting causes a big amount of pitching moment that significantly influences the UAV. In order to compensate for this effect, a feedforward term is added into the control loop. Pitch attitude control loop is presented in the Fig. 4. Adding the feedforward term increases the speed of rejection of the input disturbance caused by the tilting of rotors. The feedforward moment is proportional to the tilt angle γ_{ref}.

The pitch attitude control law is given in equation (25).

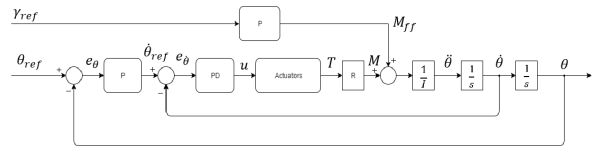

Fig. 4. Block diagram of the pitch controller loop

$$\begin{aligned} M_{ff} = K_p \cdot \gamma_{ref} e_\theta &= \theta_{ref} - \theta \\ \dot{\theta}_{ref} &= K_p \cdot e_\theta \\ e_{\dot{\theta}} &= \dot{\theta}_{ref} - \dot{\theta} \\ M_{fb} = K_p \cdot e_{\dot{\theta}} + K_i \cdot \int e_{\dot{\theta}} \cdot dt + K_d \cdot \frac{e_{\dot{\theta}}}{dt} \end{aligned} \tag{25}$$

Total virtual pitching moment is a sum of feedforward and feedback terms.

$$M = M_{ff} + M_{fb} \tag{26}$$

For roll attitude control structure a standard 2 DOF controller was used. In case of yaw rate control, a PID controller was implemented only for the yaw rate loop.

V. Simulation Results

A. Control System

Main focus is put on analysis of control of forward velocity and the effect it has on the pitch attitude. Other simulation results show that the tilting of rotors does not have a significant impact on other UAV parameters and the controller performance degradation. The changes in the state vector are rejected by the controller and net effect is insignificant.

Fig. 5 presents a step response for the change in reference forward velocity V_x. The reference value of forward velocity is filtered in order to obtain slower response of the rotors. Slowing down the tilting process, gives more time for the pitch controller to reject the input disturbance.

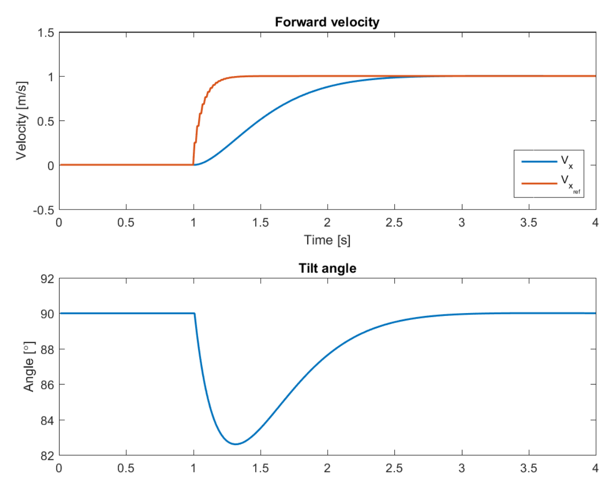

Fig. 5. Forward Velocity step response - Velocity and tilt angle

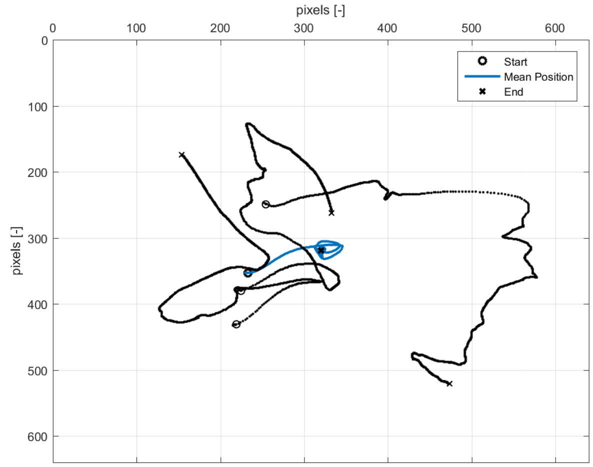

Fig. 7. Single Test- Trajectories of the targets in the image frame

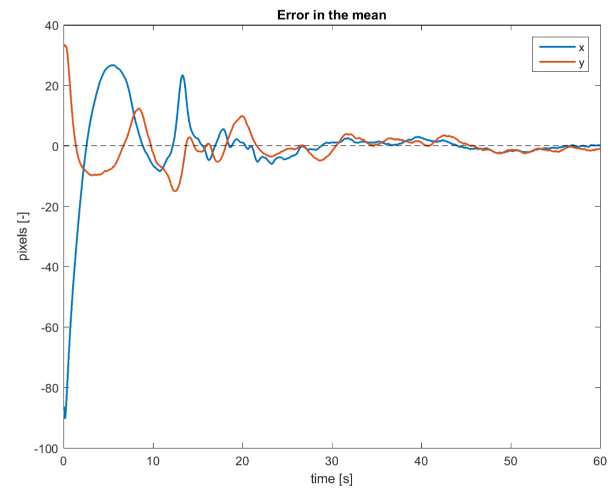

Fig. 8. Single Test - Error of the mean position of the targets

The change of pitch attitude due to tilting is presented in the Fig. 6. The change of pitch attitude is almost zero even in the presence of a large tilting angle. Without the use of a feedforward term, it was hard to obtain a satisfactory response.

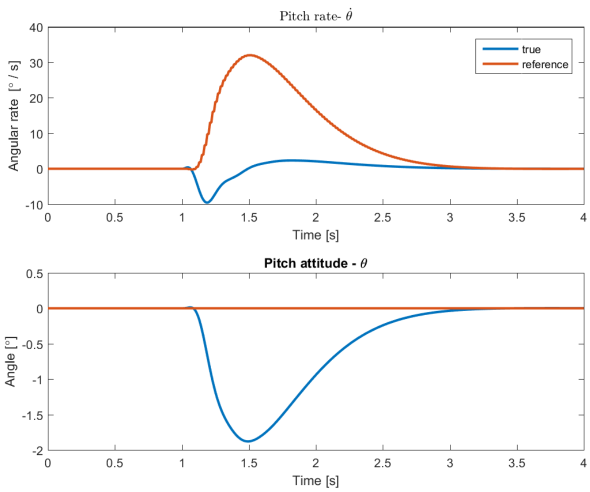

Fig. 6. Forward Velocity step response - Attitude Variables

B. Guidance System

The maximum magnitude of acceleration of the objects for the performed simulation was $a_{max} = 3\frac{m}{s}$. Simulation was run for $t_{max} = 60s$. The reference value of the spread of points was $m_d = 125$ pixels.

Fig. 7 presents the trajectories of the targets in the image. From that figure, it is visible that all the targets were maintained in the FOV of the camera through the whole time of the simulation.

Fig.7 also shows that all the targets positions in the image were kept far from the edge of the image. Even the trajectories of objects are spread all around the image, the mean position of the targets in x and y axes are kept very close to the reference centre of the image. A plot showing the error of the mean position of targets in the image is presented in the Fig. 8.

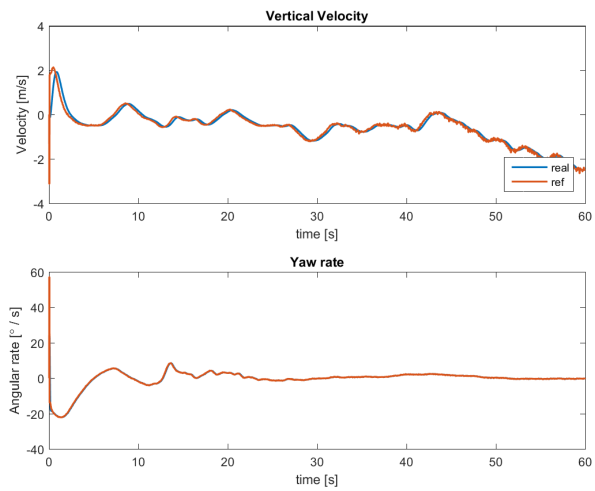

Fig. 9. Single Test - Guidance output and state obtained by the controller

From the Fig. 8 it is visible that initially, the error in both horizontal and vertical axis of the image is significant. A small overshoot in a response is observed in the starting time of the simulation. Later, error stays bounded within small limits.

The guidance outputs reference values of vertical velocity and yaw rate are presented in Fig. 9. Guidance of the UAV in its longitudinal axis is presented in the Fig. 10 and pitch attitude of the UAV is presented in the Fig. 11.

The reference values are smooth and the controller is capable of tracking the reference with high accuracy. Comparing a tilting mechanism plot from the Fig. 10 to pitch angle presented in the Fig. 11 shows that those two quantities are correlated. However, the pitch angle is a few times smaller than the tilting angle, which does not exceed a one degree during

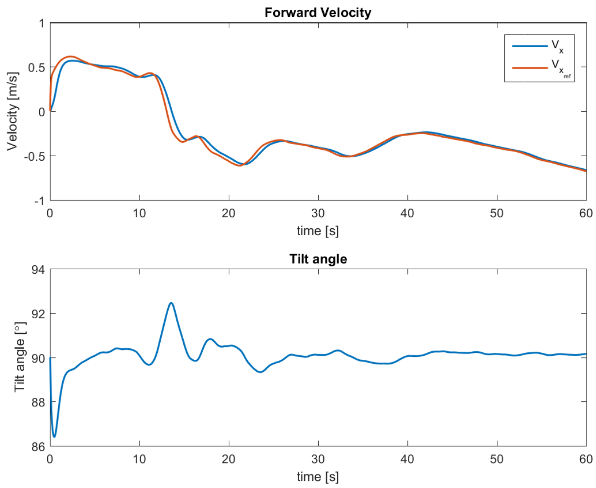

Fig. 10. Single Test - Forward velocity and tilt angle of rotors

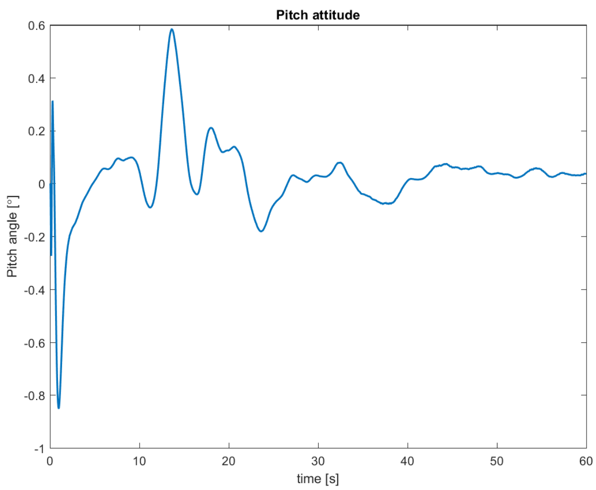

Fig. 11. Single Test - Pitch attitude during mission

Fig. 12. Two targets (green and red) configuration in the laboratory

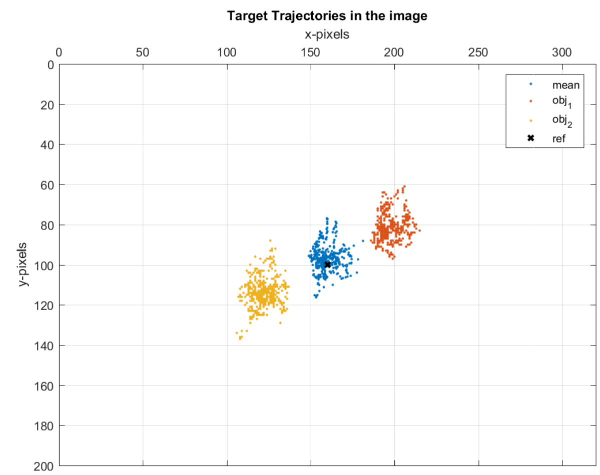

Fig. 13. Multiple Targets Tracking Flight Test - Trajectory of targets in the image

the simulation period. At that same time, the forward linear velocity of the UAV was not zero (see Fig. 10). It shows, that the UAV is capable of tracking targets while moving forward and backwards without the change of pitch attitude.

VI. Flight Tests Results

The approach used in flight tests differs slightly from the approach presented in the simulation. No linear velocity estimation was available for the controller, because the tests were performed indoor where no GPS signal was available. Ultrasonic sensor was used for estimation of the altitude of the UAV and altitude instead of vertical velocity was controlled. Attitude information was fully available to the controller from the IMU sensor. Ultrasonic and camera sensors data was filtered with a Linear Kalman Filter that significantly reduced the high frequency noise of the data.

The configuration of the targets in the lab is presented in the Fig. 12. The red and green targets were tracked based on their colour. Data collected during 40 seconds of test is presented. Fig. 13 presents the mean position of the targets in the image during the mission. Targets were static during the period of the test. There were only two tracked objects in this scenario, but the idea would be that same if there were more targets.

Fig. 13 presents the mean position of targets through the whole time of the flight test. The presented results show that the mean of targets is maintained in the image centre and at that same, two tracked objects are within the FOV.

The error of the mean is presented in the Fig. 14. The Figure shows that the tracking of the mean position of the targets is accurate. Through the majority of time, the error is not greater than 10 pixels. The increase of error in the vertical axis of the image, is correlated with the the pitch attitude change of the UAV (see Fig. 16). It concludes that the error in vertical axis is sensitive to pitch attitude changes.

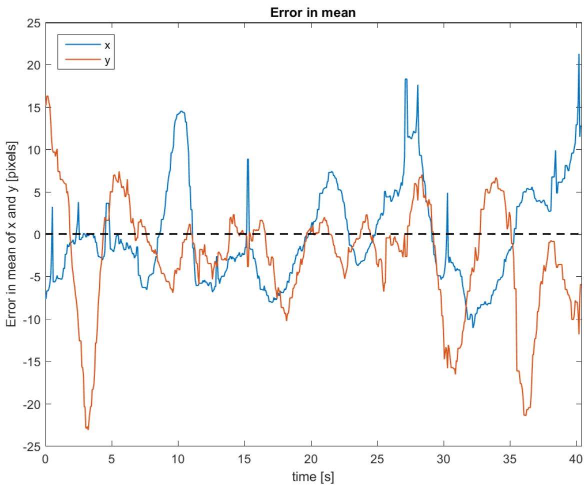

Fig. 14. Multiple Targets Tracking Flight Test - Error in mean

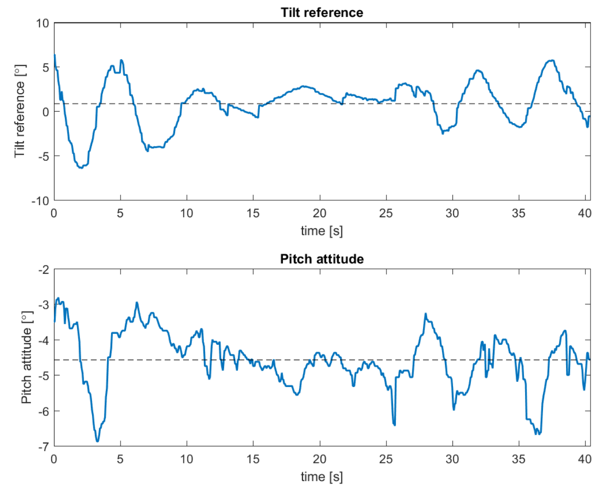

Fig. 16. Multiple Targets Tracking Flight Test - Tilt reference and pitch attitude

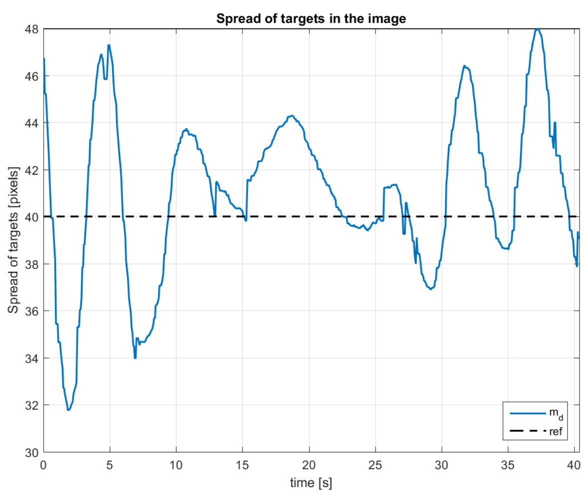

Fig. 15. Multiple Targets Tracking Flight Test - Spread of targets

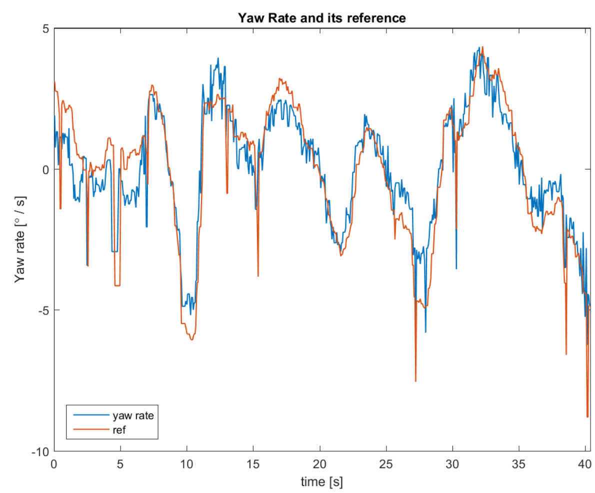

Fig. 17. Multiple Targets Tracking Flight Test - Guidance yaw rate reference following

The spread of points is presented in Fig. 15. It is visible that the error was oscillating around the reference point. It was bounded through the time of the test. The availability of the forward velocity estimate could help increase the performance. The reference tilt angle and the pitch attitude are presented in the Fig. 16.

From the Fig. 16 it is visible that pitch attitude of the UAV is affected by the tilt. However, pitch attitude does not change by a big amount during the flight. The tilting mechanism and the proposed guidance decreases the amount of pitch angle change required for forward flight and thus improves the performance of the guidance system in target tracking applications.

The two Fig. 17 and Fig. 18 show the reference commands and the actual values of yaw rate and altitude obtained by the controller. The controller gives satisfactory results.

VII. Conclusions

Presented results show that using a presented approach allows to simplify the guidance algorithm. Even though gimbal was not used, all the targets were maintained in the camera FOV. Forward movement was possible without a significant change of the pitch attitude.

Proposed guidance algorithm was capable of maintaining all the tracked targets within the camera FOV. Further development of the way of generating the forward velocity command is suggested in order to find a satisfactory method that could maintain acceptable resolution of the targets. Additional DOF added to a UAV allowed it to decrease the amount of pitch attitude change required for forward movement. Simulation and flight tests results showed that the tracking error in the vertical axis is sensitive to change of pitch angle attitude. Thus,

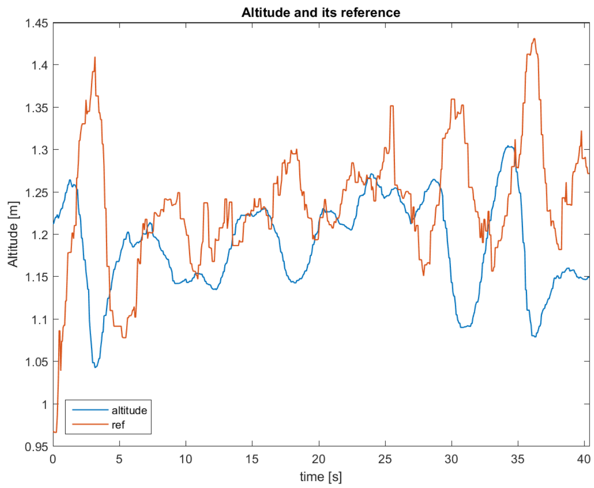

Fig. 18. Multiple Targets Tracking Flight Test - Guidance altitude reference following

any methods that ensure reference pitch angle maintenance would increase the overall objects tracking performance. The pitch attitude changes because tilting of the rotors introduces significant pitching moment into the UAV. However, a simple PID controller, with a feedforward term in pitch control loop, gives satisfactory results. PID controller also showed good performance in case of other axis of the Tilt-Rotor UAV and no significant decrease of performance was visible in other axis of the UAV while rotors where tilted.

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