Helicopter Control Algorithms from the Set Orientation to the Set Geographical Location

Zygmunt Kuś and Sławomir Fraś

Abstract. The aim of the paper was to develop helicopter control algorithms. On the basis of the results it is possible to control the unmanned helicopter by a person without pilot experience. The suggested solution is based on multilevel control. It allowed to have an effect on helicopter relocation due to setting a requested trajectory. The knowledge mentioned in the literature which concerns the behavior of the helicopter is applied to the synthesis of control system . What is more, the identification of the certain helicopter model elements was made herein. The paper presents the example of the helicopter flight to a set target location. Furthermore, the example provided in the study confirms the correct control system behavior. The possibility of introducing the set location in the coordinate system, which is connected with the ground, allows to reach the set geographical location by the helicopter in an autopilot mode.

Keywords: Unmanned Aerial Vehicle, helicopter model, step response, identification, multilevel control.

1 Introduction

The specific type of an Unmanned Aerial Vehicle (UAV) is considered in the paper. It is a 'miniature version' of a conventional helicopter with a main rotor and tail rotor. The helicopter model which was programmed in C language was used as a controlled plant. Helicopter properties are accurately described by this model. Control plant operation as a rigid body (rotational motion) and particle (translational

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motion) are faithfully represented. It also reflects most of important real helicopter behaviors. The method which was proposed by the authors undertakes the development of four control levels.

2 Helicopter Model

The helicopter as the whole may be considered as a system with four inputs and certain number of outputs. This is due to the fact that the number of the outputs depends on a number of the measured signals which are used to the helicopter control.

Figure 1 presents input signals and output signals of the helicopter model.

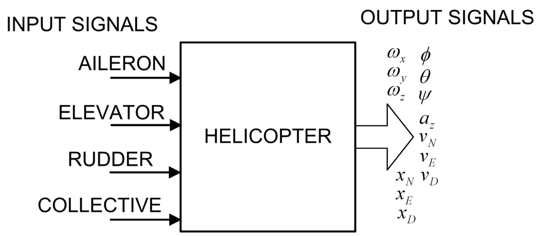

Fig. 1 Input and output signals of the helicopter model

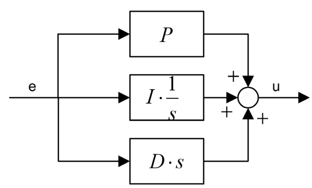

Fig. 2 PID controller

We can define three coordinate axes which are connected with the helicopter, namely longitudinal X, lateral Y and vertical Z. There are defined three angular velocities around X, Y, Z axes - ω_x, ω_y, ω_z.

Morever, we can define three coordinate axes which are connected with the ground: - these are North - x, East - y and vertical Down - z.

We assume the following signal notation:

Input signals:

AILERON $= U_{AI}$, ELEVATOR $= U_{EL}$, RUDDER $= U_{RU}$, COLLECTIVE $= U_{CO}$

Output signals:

Angular velocities: ω_x, ω_y, ω_z. The angles of rotation: Φ, Θ, Ψ. Helicopter linear accelerations: a_x, a_y, a_z. (x corresponds to North, y corresponds to East, z corresponds to Down). Helicopter linear velocities:v_N, v_E, v_D (North, East, Down). Helicopter linear locations: x_N, x_E, x_D (North, East, Down).

The helicopter is a multidimensional and non-linear plant. Therefore in the synthesis of the control system the knowledge of the main and coupling channels was applied [1], [2], [3], [4], [5].

The synthesis of the first control level uses the identification of the only selected main channels from input to output of the plant.

The idetification method based on a step response [7] was used herein.

Step responses for the selected channels from input to output of the plant are shown in Figures 2 to 4.

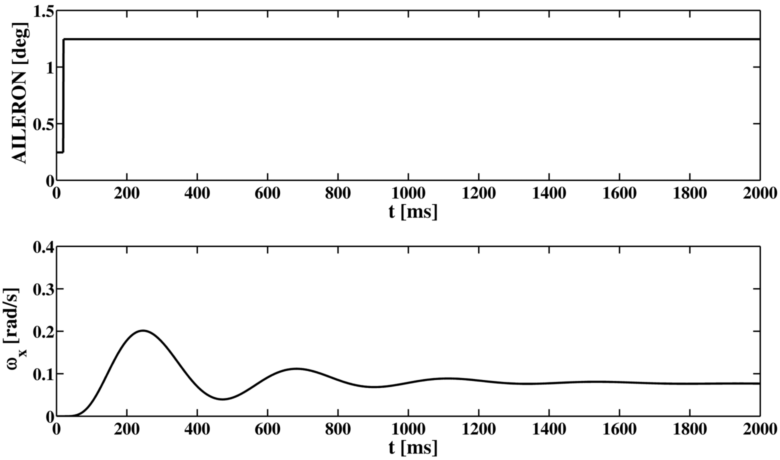

Fig. 3 The transient ω_x in the system excited by the unit step AILERON signal

Figure 2 presents a step response when the input signal is the step of AILERON signal and output signal is ω_x.

Figure 3 presents a step response when the input signal is the step of ELEVATOR signal and output signal is ω_y .

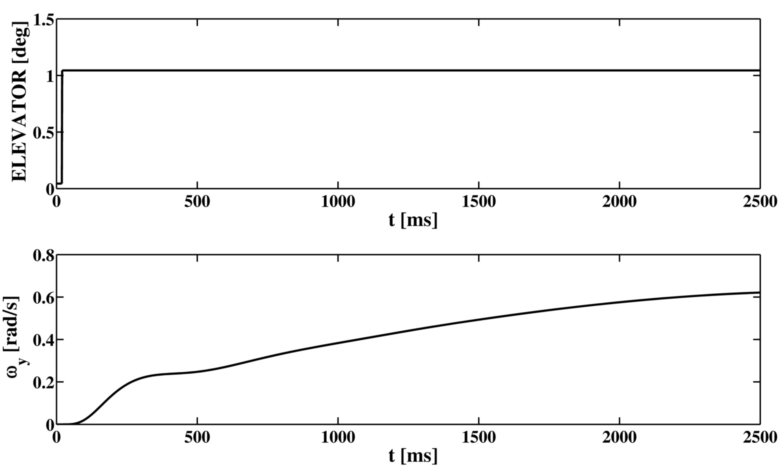

Fig. 4 The transient ω_y in the system excited by the unit step ELEVATOR signal

Figure 4 presents a step response when the input signal is the step of RUDDER signal and output signal is ω_z .

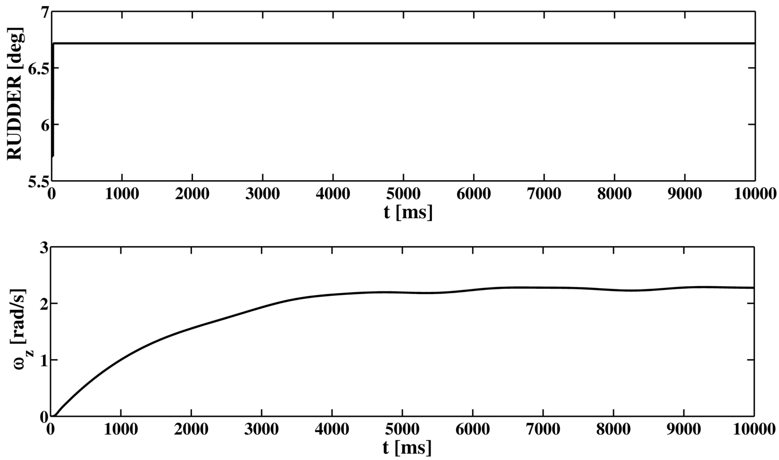

Fig. 5 The transient ω_z in the system excited by the unit step RUDDER signal

The next step is the identification of some transfer functions on the basis of the obtained step responses. These signals were used to identify transfer functions presented in (1), (2), (3) and (4). Hence we obtain transfer functions as follows:

$$K_{92}(s) = \frac{\omega_x(s)}{U_{AI}(s)} = \frac{1}{11.7 + 0.1672s + 0.05991s^2} \tag{1}$$

$$K_{103}(s) = \frac{\omega_y(s)}{U_{EL}(s)} = \frac{1 + 0.7641s}{0.1161 + 4.121s + 0.05758s^2 + 0.03567s^3} \tag{2}$$

$$K_{114}(s) = \frac{\omega_z(s)}{U_{RU}(s)} = \frac{1}{0.3427 + 0.8046s} \tag{3}$$

$$K_{45}(s) = \frac{U_{RU(s)}}{\omega_z(s)} \cdot \frac{\omega_z(s)}{U_{CO}(s)} = \frac{0.3427 + 0.9072s + 0.2408s^2}{0.3328 + 1.068s + 0.4260s^2} \tag{4}$$

The above transfer functions we obtain were obtained by means of the Matlab functions.

3 First Control Level

The first control level concentrates on angular velocity in three helicopter rotation axes.

This stage uses the identification of the selected main channels from input to output of the plant as presented above.

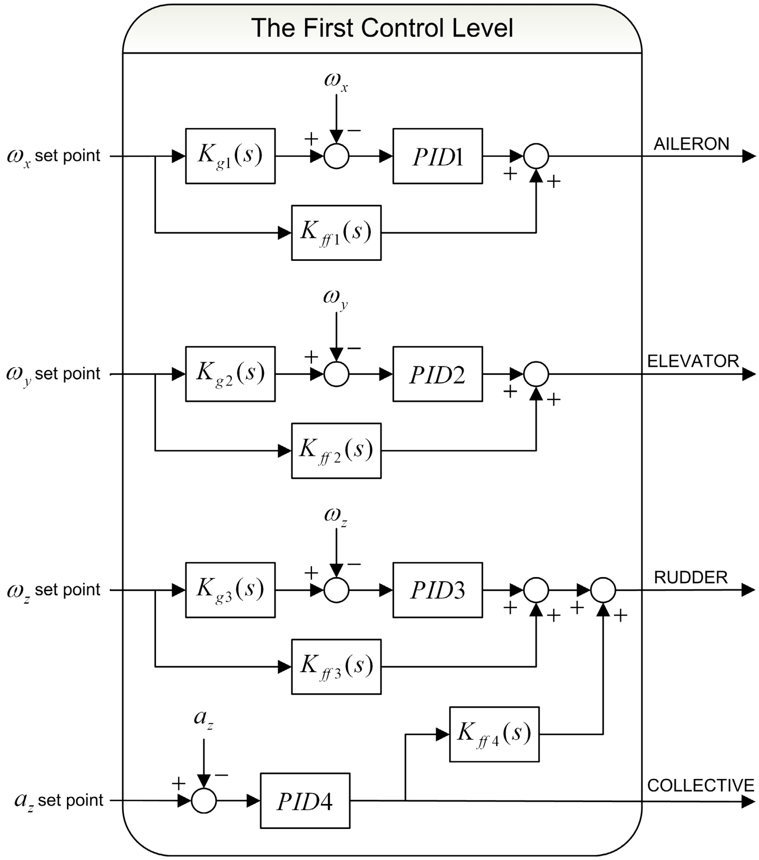

Fig. 6 The first control level

Moreover, the properties of some plant coupling channels, mentioned in the literature, are taken into account during the synthesis of control system [1], [2], [3], [4], [5].

Figure 5. presents first control level.

A feedback and a feedforward were used in the control system.

In Figure 6 a schematic diagram of PID controller is shown. Table 1 presents PID regulators settings. The regulators were tuned in a purely experimental way [6].

Table 1 PID settings

	PID1	PID2	PID3	PID4
P	2	3	9	0.5
I	2.5	30	25	10
D	0.2	0.1	0	0

Table 2 PID settings

	PID5	PID6	PID7
P	3.5	2.5	3
I	0	0	0
D	0	0	0

We use a first order lag as a filter transfer functions $K_g(s)$:

$$K_{g1}(s) = K_{g2}(s) = K_{g3}(s) = \frac{1}{(1+sT)}, \; T = 0.1$$

These transfer functions allow to obtain control signals (AILERON, ELEVATOR, RUDDER, COLLECTIVE) without sudden changes.

The feedforward transfer functions $K_{ff}(s)$ were obtained as presented below:

$$K_{ff1} = \frac{K_{g1}(s)}{K_{92}(s)}; \; K_{ff2} = \frac{K_{g2}(s)}{K_{103}(s)}; \; K_{ff3} = \frac{K_{g3}(s)}{K_{114}(s)}; \; K_{ff4} = K_{g4}(s) \cdot K_{45}(s);$$

4 Second Control Level

The second level focuses on angles of rotation control in three helicopter rotation axes.

This level is responsible for maintaining and setting the helicopter to the set orientation.

The helicopter attitude is described by three angles of rotation around X, Y, Z axes - Φ, Θ, Ψ.

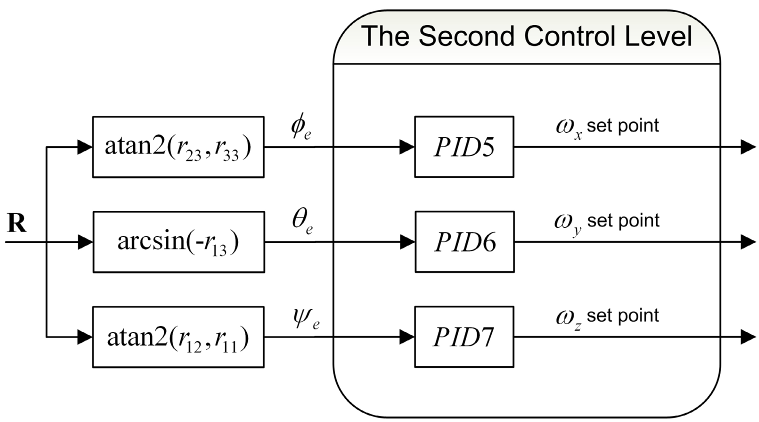

Fig. 7 The Second control level

Figure 7 presents a schematic diagram of the second control level. There is also shown the method of error angles Φ_e, Θ_e and Ψ_e calculation with using the attidude error matrix **R**.

Table 2 presents PID regulators settings. The regulators were tuned in a purely experimental way [6].

Helicopter attitude angles errors are calculated on the basis of the attitude error matrix as shown in Figure 7.

There is an additional block between second and third level which is not directly connected with control. The block transforms the data from the linear system to rotational system.

Details of the calculations are presented in Figures 7, 8 and 9.

Euler angles were also presented in a matrix form - $\mathbf{M_C}$ as shown in Figure 8. $\mathbf{M_C}$ defines current helicopter attitude. $\mathbf{M_D}$ defines set helicopter attitude.

Attitude error matrix **R** was used in this block. This matrix was built on the basis of set attitude matrix and Euler angles as was shown in Figure 8. The angles $\boldsymbol{\Phi}$, Θ and $\boldsymbol{\Psi}$ describe current helicopter attitude.

The block which was presented in Figure 9 also contains set attitude matrix . It was developed on the basis of helicopter linear set accelerations (**u**) and helicopter front set orientation (**f**). Helicopter linear set accelerations are determined in the coordinate system which is connected with the ground.

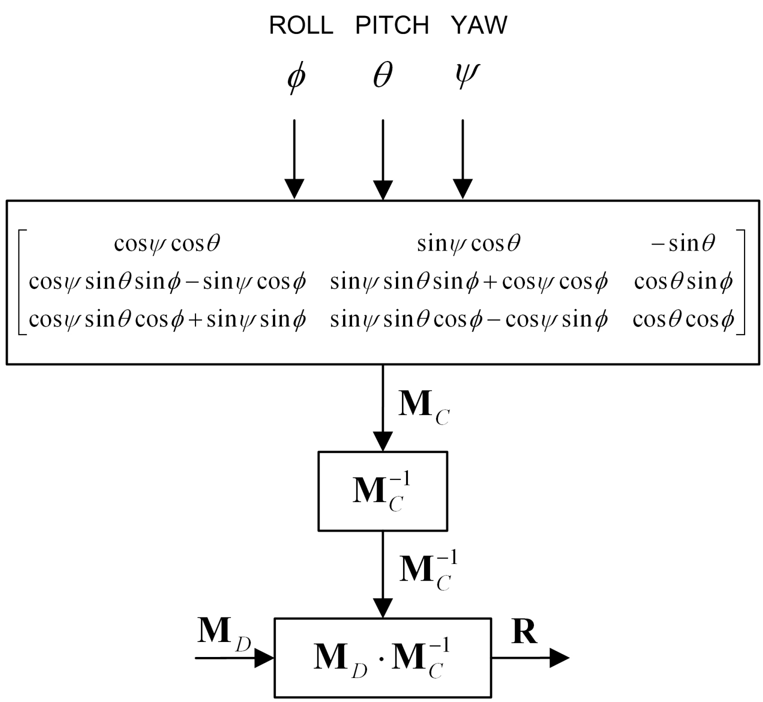

Fig. 8 The block of the orientation error matrix **R** calculation

Furtheron, attitude set matrix is calculated on the basis of the vectors **u** and **f**. These vectors determine desirable helicopter orientation. The top direction of the helicopter is defined by the vector u in the coordinate system which is connected with the ground. The vector **f** defines rotation around the *Z* axis in the coordinate system which is connected with the helicopter.

Gram-Schmidt process allows us to obtain the orthogonal vectors **u2** and **f2**. This process removes component in the specified direction without taking into account the vector length. The next step is to calculate a new vector (**f2** × **u2**) using the vector product. We obtain the unit vectors **u2**, **f2** and (**f2** × **u2**) which are result of normalization. These unit vectors describe new transformation, namely the helicopter attitude set matrix ($\mathbf{R} = [\mathbf{f2}; \mathbf{u2} \times \mathbf{f2}; \mathbf{u2}]$).

Due to normalisation we obtain the unit vectors **u2**, **f2** and (**f2** × **u2**).

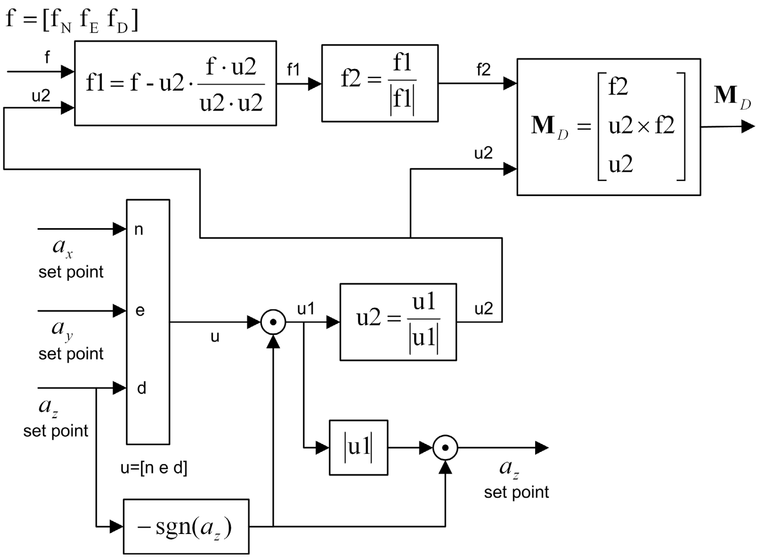

Fig. 9 The block of data transformation from the linear system to rotation system

5 Third and Fourth Control Levels

The third level of controllers calculates the set accelerations in the coordinate system which is connected with the ground. The calculations are made on the basis of the current and set helicopter velocities. All calculations are made in the same coordinate system.

The fourth level of controllers calculates the set velocities in the coordinate system which is connected with the ground. These calculations are made on the basis of the current and set helicopter locations.

Figure 10 shows a schematic diagram of the third and fourth control levels.

Table 3 presents PID regulators settings. The regulators were tuned in a purely experimental way [6].

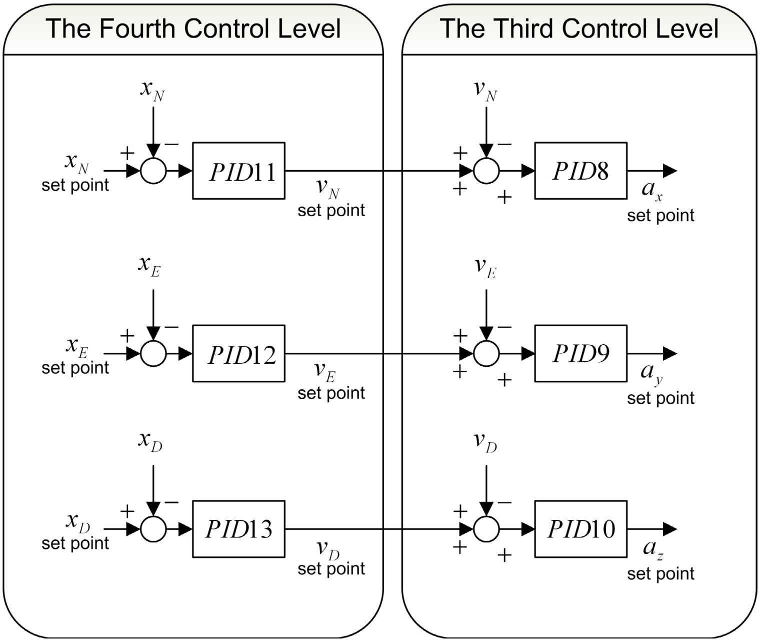

Fig. 10 Third and fourth control levels

Table 3 PID settings

	PID8	PID9	PID10	PID11	PID12	PID13
P	0.5	0.5	3	0.45	0.45	2
I	0	0	3	0	0	0
D	0	0	0	0	0	0.2

6 Examples of Helicopter Flight Symulations

Figures 11 to 13 demonstrate the example of the helicopter trajectory. The same trajectory is there shown in three axes - North-South, East-West and Down-Up.

Figure 11 presents the behavior of the helicopter during the flight. It can be observed that the current value of x_N, where x_N is the location of the helicopter along North axis, follows x_N set point.

Figure 12 presents the behavior of the helicopter during the flight. It is observed that current value of x_E, where x_E is the location of the helicopter along East axis, follows x_E set point.

Figure 13 presents the behavior of the helicopter during the flight. It is observed that current value of x_D, where x_D is the location of the helicopter along Down axis, follows x_D set point.

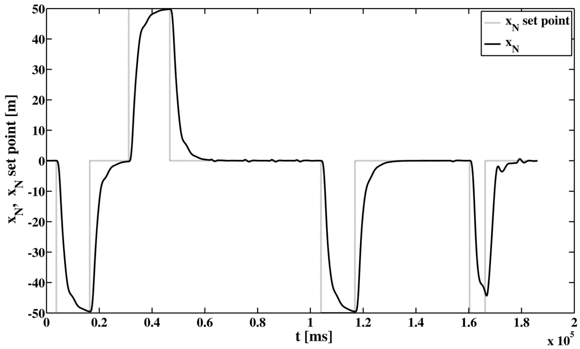

Fig. 11 The transient x_N set point and x_N during the helicopter flight

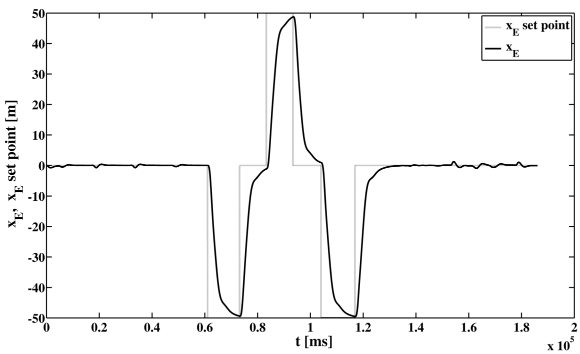

Fig. 12 The transient x_E set point and x_E during the helicopter flight

The example which was presented herein demonstrate a correct behavior of the flying helicopter model. It can be noticed that the step responses demonstrate that due to multilevel control system it is possible to achieve desired responses. In this case, the desired response to a step input is a first order response. Conclusively, it allows to achieve the 'smooth' trajectory of the flight.

Therefore the flight is safe. The small oscillations in the z axis direction, which can be observed in Figure 13, do not pose a threat for the helicopter.

The example which was presented herein demonstrates a correct behavior of the flying helicopter model.

The set trajectory consist of several step changes in the set point.

The possibility of introducing the set location in the coordinate system, which is connected with the ground, allows to reach the set geographical location by the helicopter in an auto mode.

The helicopter can track the set flight trajectory when the trajectory is built from the successive set geographical locations and the altitudes.

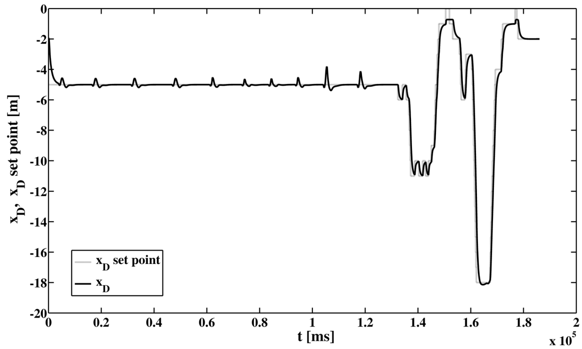

Fig. 13 The transient x_D set point and x_D during the helicopter flight

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