Laboratory Platforms for Dynamic Positioning – Modeling and Identification

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Abstract: Dynamic positioning is a challenging task in control of marine vessels, with the primary objective of maintaining a desired, predefined position of the vessel. This paper describes an overactuated laboratory platform developed at the Laboratory for Underwater Systems and Technologies with the purpose of testing control algorithms. This paper focuses on the identification of the laboratory platform. The identification method which is used is based on recording open loop step responses. Preliminary experimental results for controllable degrees of freedom are presented. The paper also describes a MOOS (mission oriented operating system) based communication structure used to control the platform.

Keywords: marine vessels, identification, MOOS, dynamic positioning

1. INTRODUCTION

Dynamic positioning (DP) in marine applications presents a challenging research area. The task of keeping a predefined position of the vessel is exacerbated by the fact that the external disturbances in marine applications are stochastic and omnipresent. The problem of dynamic positioning has been studied well in literature and has been applied on underwater vehicles, Smalwood and Whitcomb (2004), Hsu et al. (2000), and ships, Fossen (1994). Simply put, the biggest problems which arise while solving the DP problems arise from available thruster configuration and control approaches. In general, control of marine vehicles is a difficult task because of their complex mathematical model influenced by different hydrodynamic effects. Numerous simplified marine vehicle models have been developed and validated for control purposes, Caccia et al. (2000), Ridao et al. (2004). However, before any control level is designed, a reasonably accurate mathematical model has to be defined and its parameters identified. So far, the authors have performed and reported detailed identification results on underactuated remotely operated underwater vehicles, Miskovic et al. (2009a), Miskovic et al. (2007b), and autonomous surface vehicles Miskovic et al. (2009b). Based on the identified models, low–level (autopilots) and mid–level (line–following) control algorithms have been implemented for marine vehicles, Miskovic et al. (2008), Mišković et al. (2009).

The work which is presented in this paper is based on an overactuated marine surface platforms called *PlaDyPos* (see Fig. 4(a)). The platform has been developed at the Laboratory for Underwater Systems and Technologies (LabUST), University of Zagreb with the main task of research and testing of algorithms for dynamic positioning, point–to–point guidance, line–following and path–following. The desire for a unified approach to communication between different vehicles in the Laboratory and control algorithms developed in different programming languages led to integration of these systems into a MOOS–based (mission orientated operating system) communication structure. This paper gives description of the communication structure used for controlling the *PlaDyPos* laboratory platform. In addition to that, mathematical model of the platform is described and preliminary identification results of the dynamic model of the platform is presented. The model is identified on the basis of open loop step response experiments.

The paper is organized as follows. The following section describes the communication concept between the platform, control algorithms and the user interface based on a star–shaped communication structure using MOOS database. In Section III, mathematical model which is used to describe the platform is presented, while the methodology used for identification of the model parameters is elaborated in Section IV. Section V presents the preliminary identification results and the paper is concluded with Section V.

2. MOOS–BASED COMMUNICATION CONCEPT

The main communication principle is that every process publishes its output variables to the MOOS database (MOOS DB). In addition to that, if a process requires input variables, it has to subscribe to them in the MOOS DB. In other words, all communication goes through MOOS DB, therefore forming a star shaped control struc-

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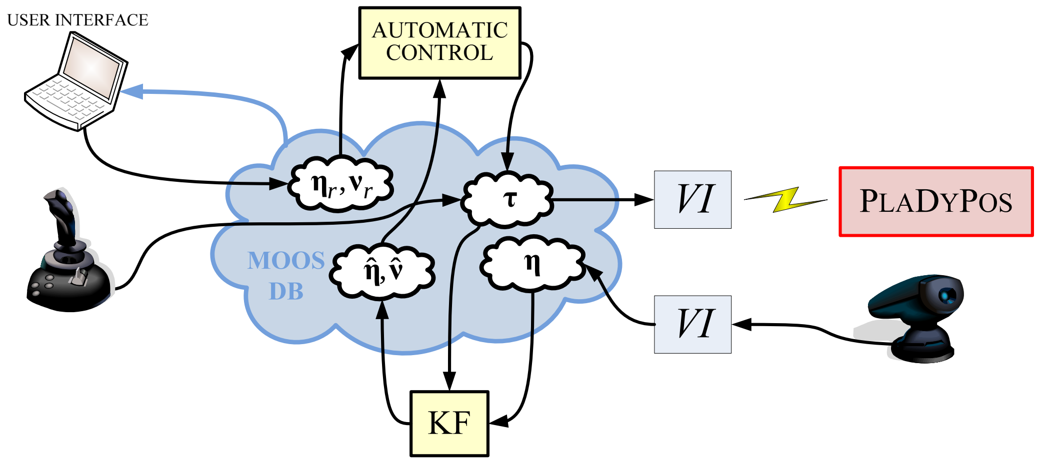


Fig. 1. Communication concept using a centralized database.

ture. The down sides of this approach are that if a fault occurs in the central node (MOOS DB), the whole system becomes faulty; and indirect communication introduces additional communication delays. However, the advantages of this structure are that it is modular in a sense that additional processes can simply be introduced in the control structure. Also, if one peripheral node (process) is faulty, the complete system need not stop executing. The following paragraph describes elementary processes (nodes) in the proposed structure, given with Fig. 1, which has been implemented.

PlaDyPos platform is connected to the base computer via a radio link. The link is developed as a LabVIEW virtual instrument (VI) and it is used to send command vector $\mathbf{n^i}$ to each thruster onboard the platform. The camera above the pool feeds image to a VI which recognizes the marker placed on the platform, extracts positions and orientation of the platform and publishes it to MOOS DB.

Command signals can be designated via joystick (manual control), or using automatic control process. In the specific case, automatic control has been programmed using LabVIEW, but the advantage of this approach is that individual process algorithms can be implemented in any programming language as long as the outputs are published in MOOS DB. Reference positions and orientations are set using user interface, which also graphically represents all published variables. Automatic control process in general case uses estimates of measured variables. These estimates are generated by some filtering (KF) process. If filtering process is not included, measured variables are mapped directly to the estimated variables. In the case of identification experiments, the user publishes commands via user interface to the MOOS DB. The response measurements are also published. Logging of all published variables is performed in the MOOS DB.

3. COMPLETE MATHEMATICAL MODEL OF THE PLATFORMS

Basic mathematical modeling scheme for marine vessels can be described with Fig. 2.

The modeling structure which is used to describe the platforms mathematical model is given in Fig. 3. The model is divided into the mathematical model of the laboratory platform, and the a priori compensation model.

The platform is actuated by using bilge pumps with propellers attached to the shaft as thrusters. Individual thruster i can be described with a simple static model where the generated thrust $\tau^{i\#}$ is a quadratic function of the rotational speed of the propeller, Fossen (1994). This model is called an affine model and it neglects the fluid flow speed through the thruster. This assumption is valid if speed of the platform is reasonably small. Each thruster is commanded via radio command n^i sent to the processors onboard the platform. These commands are in the range from -15 to 15. The motor drivers generate voltage proportional to the value of the sent commands, and the rotational speed of the propeller can be considered proportional to the applied voltage. In other words, each generated thrust τ^i is a quadratic function of the sent radio commands n^i, i.e.

$$\tau^i = K_T |n^i| n^i. \tag{1}$$

The thruster configuration in both platforms is such that the thrusters form the X configuration, as shown in Fig. 4(b). The *allocation matrix*, which gives relation between the vector of forces exerted by each thruster, $\boldsymbol{\tau}^{i\#} = \begin{bmatrix} \tau^{1\#} & \tau^{2\#} & \tau^{3\#} & \tau^{4\#} \end{bmatrix}^{\mathrm{T}}$, and thrusts and moments which act on the rigid body $\boldsymbol{\tau}^{\#} = \begin{bmatrix} X^{\#} & Y^{\#} & N^{\#} \end{bmatrix}^{\mathrm{T}}$, where $X^{\#}$ and $Y^{\#}$ are surge and sway force, respectively, and $N^{\#}$ is the yaw moment, is given with (2). From here it is obvious that the platforms are controllable in 3 degrees of freedom, and there is redundancy in the actuators.

$$\boldsymbol{\tau}^{\#} = \begin{bmatrix} \sin 45^\circ & \sin 45^\circ & \sin 45^\circ & \sin 45^\circ \\ -\sin 45^\circ & \sin 45^\circ & \sin 45^\circ & -\sin 45^\circ \\ d & -d & -d & d \end{bmatrix} \boldsymbol{\tau}^{i\#} \tag{2}$$

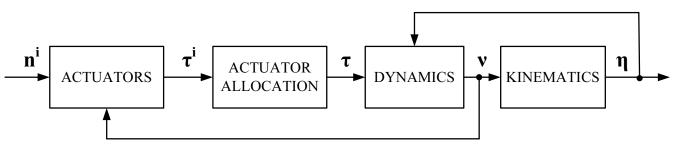


Fig. 2. Block-diagram of a general mathematical model.

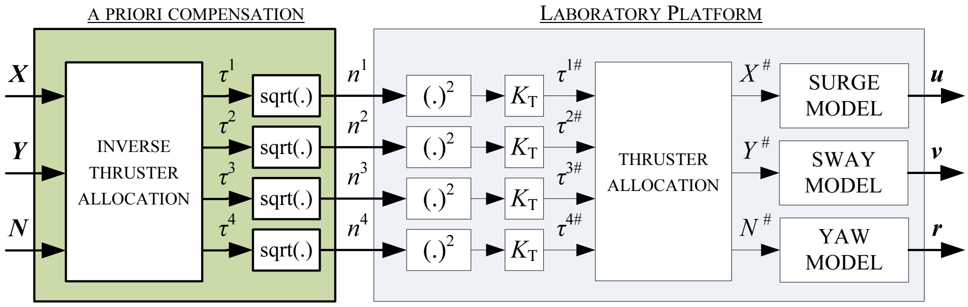


Fig. 3. The modeling structure of the laboratory platform with the a–priory compensation block.

A general single degree of freedom *dynamic equation* can be written as (3) where the speed vector is $\nu = [\,u\ v\ r\,]^{\mathrm{T}}$, with surge, sway and yaw speed, respectively.

$$\alpha_\nu \dot{\nu}(t) + \beta(\nu) \cdot \nu(t) = \delta + \tau(t) \tag{3}$$

An assumption is made that in a general case drag $\beta(\nu)$ can obtain one of the two values: $\beta(\nu) = \beta_\nu$ for constant drag and $\beta(\nu) = \beta_{\nu\nu}|\nu|$ for linear drag.

The *kinematic model* gives relations between speeds $\nu = [\,u\ v\ r\,]^{\mathrm{T}}$ defined in the body fixed frame $\{\mathrm{B}\}$ and derivatives of the position vector $\dot{\eta}$ defined in the Earth–fixed frame $\{\mathrm{E}\}$. This relation is given with (4) where ψ is the orientation of the platform.

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\psi} \end{bmatrix} = \begin{bmatrix} \cos\psi & -\sin\psi & 0 \\ \sin\psi & \cos\psi & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} u \\ v \\ r \end{bmatrix} \tag{4}$$

The a priori compensation block is designed in order to deal with the thruster allocation problem and to compensate for the nonlinear thruster characteristic. From Fig. 3 it is clear that the inputs to this block are commanded thrusts $\boldsymbol{\tau} = [\,X\ Y\ N\,]^{\mathrm{T}}$ and the outputs are signals sent via the radio link to the platform, $\mathbf{n^i} = [\,n^1\ n^2\ n^3\ n^4\,]^{\mathrm{T}}$.

4. IDENTIFICATION

The methodology which is used for identification is based on open loop step responses of the system. This method is appropriate for laboratory conditions where external disturbances are negligible. The main assumption which is used in the paper is that the dynamic model of each degree of freedom can be approximated using only constant or linear drag term. This assumption has proved to be valid in many of the authors papers before, Miskovic et al. (2007a), Mišković et al. (2009) and other available literature, Caccia et al. (2000), Ridao et al. (2004). For the linear model of surge degree of freedom, the step response can be explicitly expressed as

$$u(t) = \frac{X}{\beta_u}\left(1 - e^{-\frac{\beta_u}{\alpha_u}t}\right), \tag{5}$$

from where it follows that the drag coefficient can be determined based on the steady state response as

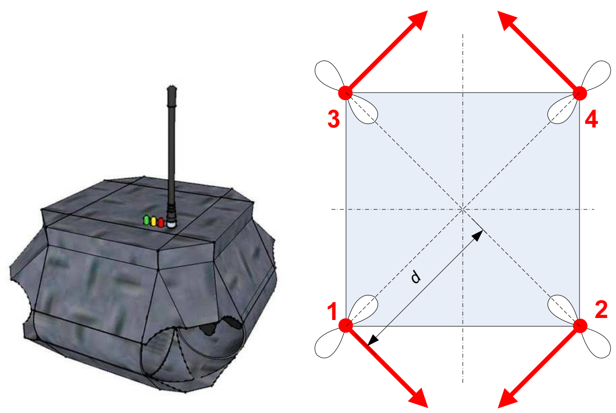
$$\beta_u = \frac{X}{u_{ss}}, \tag{6}$$

where $u_{ss} = u(\infty)$. The inertia parameter can be determined easily from the time constant of the linear system. It is well known that the time constant is equal to the time instance when the output reaches 63% of the steady state value. Once this time constant is determined from the step response, inertia parameter can be calculated using

$$\alpha_u = T_L \beta_u. \tag{7}$$

The same procedure can also be applied to any other degree of freedom for which step response is recorded.

For the nonlinear model of surge degree of freedom, the step response can be explicitly expressed as



(a) (b)

Fig. 4. (a) *PlaDyPos 2* and (b) the x–shape thruster configuration.

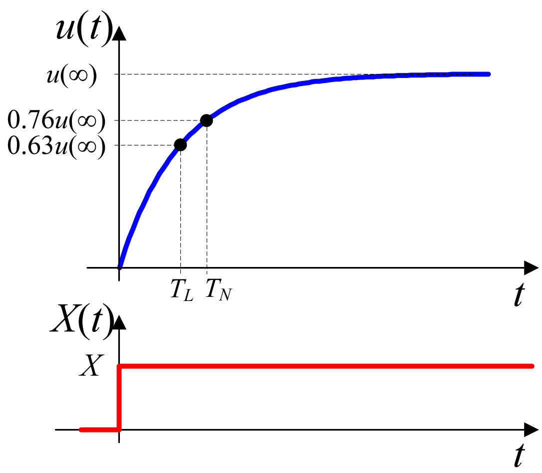


Fig. 5. Response during the open loop identification procedure.

$$u(t) = \sqrt{\frac{|X|}{\beta_{uu}}} \tanh \left[\mathrm{sgn}(X) \frac{\sqrt{\beta_{uu}|X|}}{\alpha_u} t \right], \quad (8)$$

from where it follows that the drag coefficient can be determined based on the steady state response as

$$\beta_{uu} = \frac{|X|}{u_{ss}^2}, \quad (9)$$

where $u_{ss} = u(\infty)$. The inertia parameter can be determined similarly to the procedure which is used for linear systems. An equivalent time constant in this case can be defined as

$$T_N = \frac{\alpha_u}{\sqrt{\beta_{uu}|X|}}. \quad (10)$$

At the time instance $t = T_N$ the step response reaches about 76% of the steady state value, i.e.

$$u(T_N) = u_{ss} \tanh 1 = 0.761 u_{ss}.$$

In other words, if the time instance at which the output reaches about 76% of the steady state value is recorded, inertia can be determined using (10). The same procedure can also be applied to any other degree of freedom for which step response is recorded.

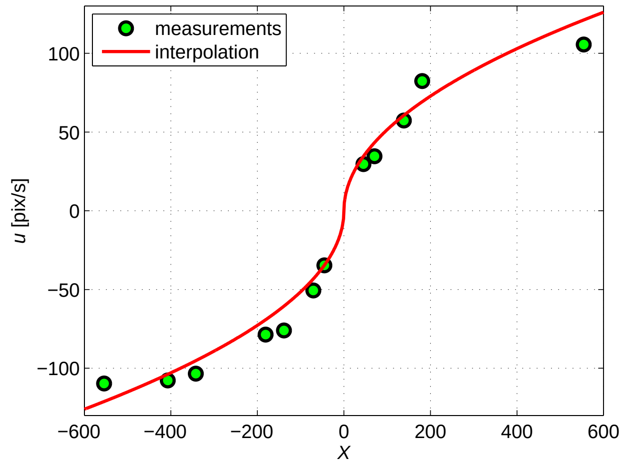
It should be noted that, unlike in the case of linear model where the equivalent time constant is constant regardless of the input step value, for the case of nonlinear model this constant is dependant on the input signal: the smaller the step input, the longer will it take for the system to reach the steady state value.

5. EXPERIMENTAL RESULTS

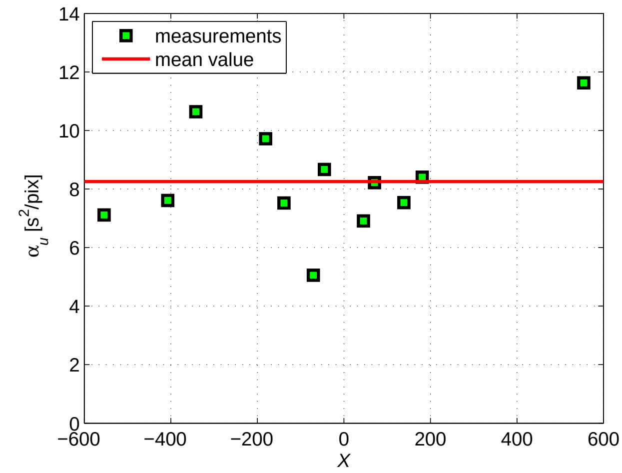
The identification of the platform was performed in the laboratory pool at the Laboratory for Underwater Systems and Technologies, University of Zagreb using an apparatus which has been first introduced in Miskovic et al. (2007a). It is based on image analysis from the camera placed above the pool. From the image, the platforms positions and orientation within the camera frame are recorded and the vector of measurements $\boldsymbol{\eta}_m = [\, x_m \; y_m \; \psi_m \,]^{\mathrm{T}}$ is obtained. Using the kinematic model given with (4), speeds within the body–fixed coordinate frame are calculated. Given the obtained velocities and normalized (dimensionless) input forces X, Y and yaw moment N, the procedure described in the previous section is used to determine drag (β_u, β_v, β_r, β_{uu}, β_{vv}, β_{rr}) and total inertia (α_u, α_v, α_r) parameters of surge, sway and yaw degree of freedom, respectively. Since the platform is symmetric relative to the surge and sway axis, only surge and yaw motion are identified, and sway dynamics is assumed to be equal to the surge dynamics, i.e. $\alpha_u = \alpha_v$, $\beta_u = \beta_v$ and $\beta_{uu} = \beta_{vv}$.

Table 1 gives all the variables which appear in the model together with their dimensions, in the form that is obtained using the identification procedure.

The identification procedure was conducted in such a way that surge and yaw degrees of freedom were excited with step input signals, and surge and yaw speed were recorded.



(a)



(b)

Fig. 6. Identification results of the surge (sway) (a) drag and (b) inertia parameters. Green circles and squares represent measurements, while the red line is the interpolated curve which fits the model.

5.1 *Surge (sway) model*

The surge model is obtained so that the platform is excited with a constant commanded surge force and forced to move across the camera image for as long as possible. Multiple step responses' steady states were used to determine the drag coefficient of the surge (sway) dynamic model and the results are shown in Fig. 6(a). It is clear from the results that the linear drag (nonlinear model) describes the behavior of the platform in a satisfactory manner and therefore (9) is used to calculate the drag coefficient. Further on, (10) is used to determine the the inertia parameter. Fig. 6(b) shows the results and the mean value of the results. Numerical results with standard deviations are given in Table 2.

5.2 *Surge (sway) model*

The yaw model is obtained so that the platform is excited with a constant commanded yaw moment and forced to

Table 1. Notation.

VARIABLE	DIMENSION	DESCRIPTION
x_m, y_m	[pix]	position in the camera frame
ψ_m	[rad]	orientation in the camera frame
u, v	$\left[\frac{\text{pix}}{\text{s}}\right]$	surge and sway speed in the {B} frame
r	$\left[\frac{\text{pix}}{\text{s}}\right]$	yaw rate in the {B} frame
X,Y,N	dimensionless	commanded forces and moments on rigid body
$\boldsymbol{\tau}^i$	dimensionless	vector of commanded thrusts for each thruster
$\boldsymbol{n}^i$	dimensionless	vector of commanded inputs for each thruster
$\boldsymbol{\tau}^{i\#}$	[N]	thrust generated from each thruster
$X^{\#}$, $Y^{\#}$	[N]	thrusts acting on the rigid–body
$N^{\#}$	[Nm]	moment acting on the rigid–body
α_u, α_v	$\left[\frac{\text{s}^2}{\text{pix}}\right]$	total surge and sway inertia
β_u, β_v	$\left[\frac{\text{s}}{\text{pix}}\right]$	surge and sway constant drag
β_{uu}, β_{vv}	$\left[\frac{\text{s}^2}{\text{pix}^2}\right]$	surge and sway linear drag
α_r	$\left[\frac{\text{s}^2}{\text{rad}}\right]$	total yaw inertia
β_r	$\left[\frac{\text{s}}{\text{rad}}\right]$	yaw constant drag
β_{rr}	$\left[\frac{\text{s}^2}{\text{rad}^2}\right]$	yaw linear drag

Table 2. Drag and inertia parameters obtained from the identification experiments.

	YAW		SURGE (SWAY)	
	α_r	β_{rr}	$\alpha_u = \alpha_v$	$\beta_{uu} = \beta_{vv}$
	$\left[\frac{\text{s}^2}{\text{rad}}\right]$	$\left[\frac{\text{s}^2}{\text{rad}^2}\right]$	$\left[\frac{\text{s}^2}{\text{pix}}\right]$	$\left[\frac{\text{s}^2}{\text{pix}^2}\right]$
MEAN	87.68	48.83	8.252	0.0378
ST. DEV. [%]	17.84	30.81	21.37	29.85

rotate around its axis, making sure it does not leave the field of view of the camera placed above the pool. Just as in the case of the surge model, multiple step responses' steady states were used to determine the drag coefficient of the yaw dynamic model and the results are shown in Fig. 7(a). It is clear from the results that the linear drag (nonlinear model) describes the behavior of the platform in a satisfactory manner and therefore (9) is used to calculate the drag coefficient. Again, (10) is used to determine the the inertia parameter (variables should be modified in order to apply them on the yaw model). Fig. 7(b) shows the results and the mean value of the results. Numerical results with standard deviations are given in Table 2.

The standard deviations obtained in the surge and yaw experiments show that the identified model gives parameters which are accurate enough to use them for control purposes.

6. CONCLUSIONS AND FUTURE WORK

This paper presents an open loop step response identification method which is applied to a laboratory platform for dynamic positioning. The mathematical model of actuating thrusters, thruster allocation and dynamic behavior of the platform is described and the parameters are identified correspondingly. The experiments are conducted in such a way that sway and yaw degree of freedom are excited separately. Sway motion is assumed to be equivalent to the surge motion due to the construction of the platform. The consistency in the obtained parameters shows that the results are satisfactory for control design purposes. In addition to that, a brief description of the communication structure based on MOOS is described. The results which are presented in this paper are preliminary. Further steps include:

- thruster mapping for understanding the real commanded thrust values,
- the platform's surge and sway velocities have to be expressed in metric dimensions,
- detailed validation procedure has to be performed and
- surge and sway motion equivalence has to be proved experimentally.

Once the detailed identification experiments are done, control algorithms (autopilots, line following controllers) which have been tested on the simulation model of the platform and have already been applied to other vehicles will be tested. As the final stage, dynamic positioning algorithms will be implemented.

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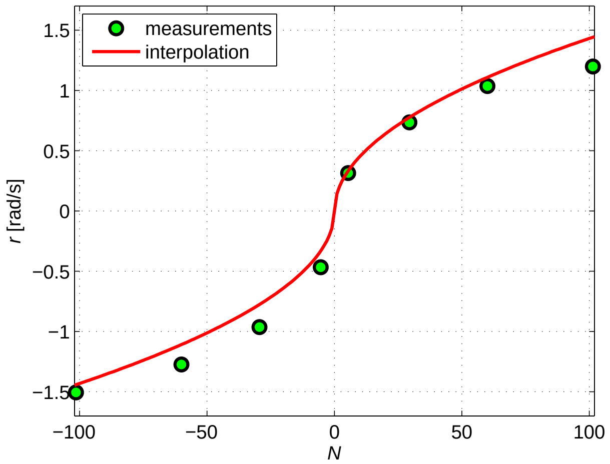
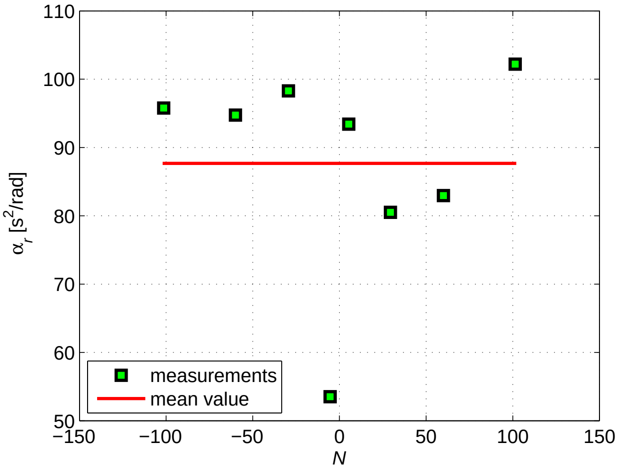


(a)



(b)

Fig. 7. Identification results of the yaw (a) drag and (b) inertia parameters. Green circles and squares represent measurements, while the red line is the interpolated curve which fits the model.

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