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Disturbance observer-assisted hybrid control for autonomous manipulation in a robotic backhoe

Automation of earth moving machineries is a widely studied problem. This paper focusses on one of the main challenges in automation of the earth moving industry, estimation of loading torque acting on the machinery. Loading torque acting on the excavation machinery is a very significant aspect in terms of both machine and operator safety. In this study, a disturbance observer-assisted control system for the estimation of loading torque acting on a robotic backhoe during excavation process is presented. The proposed observer does not use any acceleration measurements, rather, is proposed as a function of joint velocity. Numerical simulations are performed to demonstrate the effectiveness of the proposed control scheme in tracking the reaction torques for a given dig cycle. Co-simulation experiments demonstrate robust performance and accurate tracking of the proposed control in both disturbance torque and position tracking. Further, the performance and sensitivity of the proposed control are also analyzed through the help of performance error quantifiers, the root-mean-square (RMS) values of the position and disturbance tracking errors.

1. Introduction

Automation and remote control of excavator backhoes has always been a topic of interest for the earth moving industry. With automation and robotics, remarkable progress has been made in earth moving industry in terms of quality of operation [1], trajectory tracking [2, 3], fuel efficiency and operator safety [4–6], however, a completely autonomous commercial backhoe has not been deployed

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till date. In the case of an operator assisted earth moving tasks, the machinery follows a particular digging trajectory based on the operator commands. Mostly, the operator sits at a remote site and works with the help of visual feedbacks from cameras deployed at the site or simulators that mimics the real excavator motion. These feedbacks are insufficient for an efficient operation and there always exist chances of damage to machinery. This can only be avoided if the operator gets proper feedback in terms of variation in bucket load, nature of ground-bucket interaction, nature of loading torque etc. [7].

Various studies have contributed to the development of controllers to deal with the uncertainties in excavation. To enhance the efficiency of autonomous operations, non-linear controllers reported showed robustness to payload variations [8] and unknown joint-dynamics [9]. Also, studies reporting the application of impedance control [10], sliding mode control [11] and robust observers [12] has shown the possibility to achieve compliant motion in the remote control of excavators. A position-based impedance control, implemented on a mini excavator, demonstrated good accuracy in autonomous earthmoving tasks [13, 14]. The emphasis over the safety of operation in the unpredictable and complex nature of the working environment has made semi-autonomous or operator assisted tele-operations popular. Many studies have been conducted to enhance the operator assistance function in robotic backhoe operation. Implementation of haptics technology has shown to be a promising aspect in increasing operator performance and efficiency [15, 16]. Force feedback based on haptic joysticks were reported to create a sense of realism, in the operators which help to adapt, especially novices, to the working environment [17].

In this study, we address a significant challenge faced in automation of the earth moving operation, estimation of loading torque acting on the machinery. A disturbance observer-assisted control system is developed to estimate the reaction torque during earthmoving task like digging. Estimation of loading torque is significant as in any operator-assisted earth moving operation, the nature of ground resistance determines the operator command and hence, the digging trajectory. When the ground resistance is too high, the joint reaction forces or ram forces become excessively large. This may damage the machinery or even cause wheel slip especially known with novices [18]. The control system proposed can estimate the loading torque acting during excavation and compensates it.

The paper is organized as follows. Section 2 describes the dynamic modeling of the robotic backhoe followed by a problem identification section. Section 3 introduces the proposed controller design and its closed-loop system stability analysis for slowly varying disturbances with the help of Lyapunov's direct method. Section 4 presents the results and discussion of the study with simulation and co-simulation experiments. Section 5 discusses the conclusions and future scope of the paper.

2. Modelling of robotic backhoe

The robotic backhoe can be considered as a rigid link manipulator with four revolute joints, where the axis of the swing joint is normal to the ground and the other three joint axes are parallel to the ground. Fig. 1 gives the coordinate frame arrangements along with the joint angle representation of the robotic backhoe.

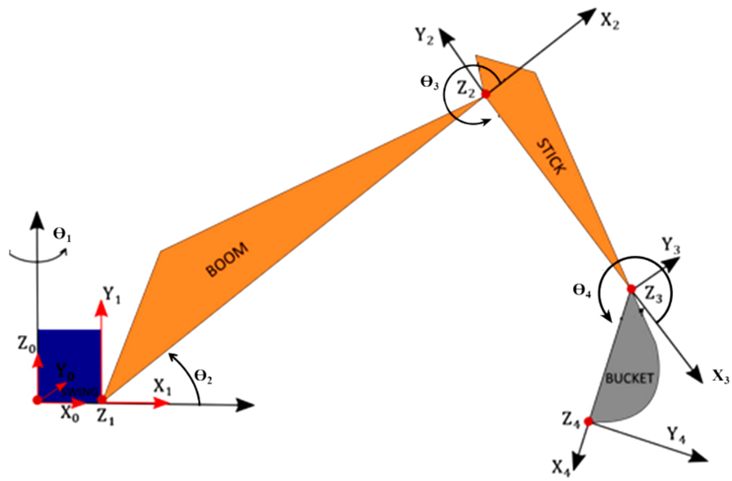


Fig. 1. Coordinate frame arrangement along with joint angle representation of the robotic backhoe

The kinematic parameters of the backhoe based on Denavit-Hartenberg (DH) representation are given in Table 1. The transformation matrix T of the end frame with respect to the base frame can be obtained by multiplying individual homogeneous transformation matrices A_i where $i = 1, 2, 3, 4$. The equations of motion of the robotic backhoe is derived by using Euler–Lagrange equations [19].

Table 1.

DH parameters for the robotic backhoe

Joint #	Link length a_i	Joint angles θ_i	Joint twist d_i	Joint offset α_i
1	a_1	θ_1	0	90°
2	a_2	θ_2	0	0
3	a_3	θ_3	0	0
4	a_4	θ_4	0	0

Dynamic equation for the robotic backhoe can be expressed as,

$$M(q)\ddot{q} + H(q,\dot{q})\,\dot{q} + G(q) = \tau - \tau_{dis}\,, \tag{1}$$

where $M(q) \in R^{m\times m}$ is the inertia matrix which is a positive-definite symmetric matrix $H(q,\dot{q}) \in R^{m\times m}$ represents the Coriolis and centrifugal forces, $G(q) \in R^m$

is the gravity matrix of the reduced system. $q = [q_1\ q_2\ q_3\ q_4]^T$ represents the joint space position vector. The joint torque vector is denoted by τ and $\tau_{dis} = [\tau_{dis1}, \tau_{dis2}, \tau_{dis3}, \tau_{dis4}]$ represents the loading torque vectors acting on the joints. During digging, the generalized force vector acting on the bucket is taken as F_L. The Jacobian matrix, $J(q)$ converts the bucket loading force F_L into the loading torque acting on the joints. This can be expressed as:

$$\tau_{dis} = J(q)^T F_L\,. \tag{2}$$

Several modelling approaches had been adopted for predicting the nature of the loading force acting on the bucket, during soil-tool interaction. For the study, the soil-tool modelling approach has been taken from [20, 21]. Fig. 2 shows the bucket interaction with the soil during digging.

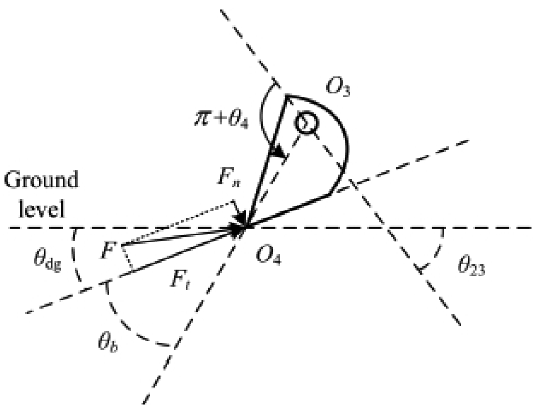


Fig. 2. Soil-bucket interaction during digging

In this approach, the loading torque is given as,

$$\tau_{dis} = \begin{bmatrix} \tau_b \\ a_2\left[F_t \sin\left(\theta_2 - \theta_{dg}\right) - F_n \cos\left(\theta_2 - \theta_{dg}\right)\right] \\ a_3\left[F_t \sin\left(\theta_{23} - \theta_{dg}\right) - F_n \cos\left(\theta_{23} - \theta_{dg}\right)\right] \\ a_4\left(-F_t \sin\theta_b + F_n \cos\theta_b\right) \end{bmatrix}, \tag{3}$$

where, F_t and F_n denote the tangential and normal components of the reaction force in the soil-bucket interaction. τ_b is not considered in the study as θ_1 remains constant during digging operation. The reaction force F_r, is defined parallel to the direction of digging. F_t and F_n are calculated as,

$$\begin{aligned} F_t &= F_r \cos\left(\theta_{dg} - \beta\right), \\ F_n &= -F_r \sin\left(\theta_{dg} - \beta\right), \qquad 0.1 \leqslant \beta \leqslant 0.45, \end{aligned} \tag{4}$$

where β is a dimensionless coefficient and the value is held constant at as 0.1. The reaction force F_r, is calculated as,

$$F_r = k_p \left[k_s bh + \mu N + \varepsilon \left(1 + \frac{v_s}{v_b} \right) v_d \right]. \tag{5}$$

In equation (5), k_p and k_s are the specific resistance to cutting. ε and μ denotes the coefficient of resistance during bucket filling and the coefficient of friction of bucket and ground, respectively. Ndenotes the pressure force exerted by bucket on soil. v_s, v_b and v_d are the volume of prism of soil, volume of bucket, respectively, and amount of the soil inside the bucket.

3. Control of robotic backhoe

The main objective of this paper is to develop a control system that can estimate the loading torque occurring on the backhoe during an autonomous excavation task while tracking the desired digging trajectory. Such an approach could remarkably contribute toward force-reflective operation in remote controlled or autonomous operation of the backhoe. As it is difficult to design a feedback controller that could estimate the high force transients occurring during a soil-moving task [22] (due to their narrow bandwidth), a combination of disturbance observer with a non-linear control technique is explored in this paper. Studies addressing a combination of non-linear controllers with disturbance observer for robust tracking of robotic manipulators are presented in [23, 24]. The proposed method showed improved tracking performance in the case of robotic manipulators. As there exist many parallels between a robotic manipulator and a robotic backhoe, in this study we explore a similar approach with a combination of a non-linear controller, like a computed torque control (CTC), and disturbance observer (DOB) in counteracting the effects of the disturbances. Similar attempts to estimate the resistive forces using a DOB and modelling the repetitive part using an iterative learning control (ILC) in a 1.5-ton excavator was proposed in [25]. Results obtained demonstrated strong tracking in the case of both repetitive and non-repetitive disturbances. This study is an attempt to ensure robustness in an autonomous or remote-controlled excavation task without the need for an accurate soil-bucket interaction model. Moreover, the study is highly relevant as it could enhance operator and machine safety during the excavation task.

3.1. Design of the control system

For the robotic backhoe, the following nonlinear control law is proposed,

$$\tau = \widehat{M} \left(\ddot{q}_d + K_p e + K_d \right) + \widehat{N} \left(q, \dot{q} \right) - \hat{\tau}_{dis}, \tag{6}$$

where $\widehat{M}(q)$ and $\hat{\tau}_{dis}$ denote the estimates of $M(q)$ and τ_{dis}, and $\widehat{N}(q, \dot{q})$ represents the estimates of $\widehat{H}(q, \dot{q})\,\dot{q}$ and $\widehat{G}(q)$. The block diagram of the overall system is shown in Fig. 3. The disturbance observer is applied to all the joints to estimate the loading torque acting at each joint during digging. The control torque generated from equation (6) will bring the robotic backhoe to follow the desired trajectory while the DOB suppresses the disturbance estimated on the system achieving a hybrid control in the desired dig cycle.

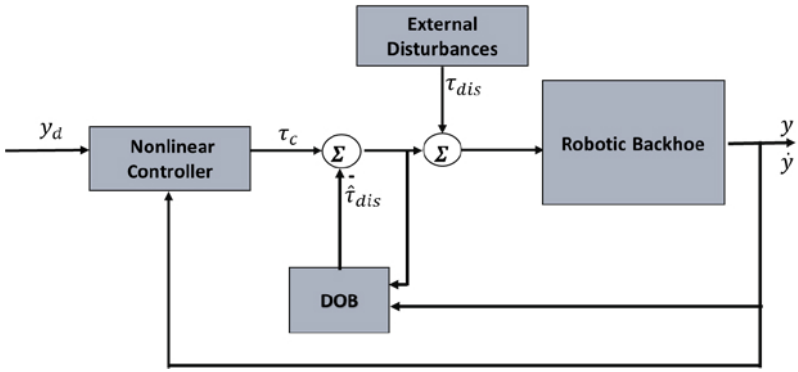


Fig. 3. Control system proposed for the hybrid control of the robotic backhoe

$\hat{\tau}_{dis}$ is an estimate of the loading torque vector, τ_{dis}, which is obtained from equation (2). The desired trajectory to be tracked is denoted by y_d. In the control system, the disturbance observer estimates the reaction torque and provides a feed-forward compensation to counteract the effect of the disturbance torque. In many of the robotic systems, unavailability of accurate accelerometers poses a big problem [26]. As velocity signals are mostly corrupted by noise signals, differentiating it to obtain acceleration values might not be accurate.

The proposed observer does not require acceleration measurements. Here the estimate of the disturbance torque, $\hat{\tau}_{dis}$ is proposed as a function of joint velocity i.e. $\hat{\tau}_{dis} = f(\dot{q})$. $\hat{\tau}_{dis}$ can be expressed as:

$$\hat{\tau}_{dis} = K_0 \widehat{M}(q)\dot{q} + \eta, \tag{7}$$

where η is an arbitrary vector. Choosing $\dot{\eta}$ as,

$$\dot{\eta} = -K_0 \left(\tau - \widehat{N}\,(q, \dot{q}) + \hat{\tau}_{dis}\right), \tag{8}$$

where K_0 is a positive gain matrix. The adaption laws for the disturbance estimate vector is chosen as,

$$\dot{\hat{\tau}}_{dis} = -K_0 \tilde{\tau}_{dis} \,. \tag{9}$$

The observer error vector is,

$$\tilde{\tau}_{dis} = \tau_{dis} - \hat{\tau}_{dis} \,. \tag{10}$$

Remark 1: The disturbance τ_{dis} is bounded such that there exists a vector $\tau_L > 0$ such that $0 \leqslant |\tau_{dis}| \leqslant \tau_L$.

Remark 2: Rate of change of disturbances and system uncertainties are negligible when compared to the slowly varying disturbance. Therefore $\dot{\tau}_{dis} \approx 0$. From equation (9) and (10)

$$\dot{\hat{\tau}}_{dis} = -K_0 \left(\tau_{dis} - \hat{\tau}_{dis}\right). \tag{11}$$

The closed-loop stability and error convergence for the proposed observer is considered with Lyapunov's direct method as

$$V = \frac{1}{2} \left(\tau_{dis} - \hat{\tau}_{dis}\right)^2. \tag{12}$$

From above equations (10) and (11) and taking the time derivative of equation (12), the following equation is obtained

$$\dot{V} = \left(\tau_{dis} - \hat{\tau}_{dis}\right)\left(\dot{\tau}_{dis} - \dot{\hat{\tau}}_{dis}\right), \tag{13}$$

then the update law from equation (11) ensures that

$$\dot{V} = \left(\tau_{dis} - \hat{\tau}_{dis}\right)\left(-K_0 \left(\tau_{dis} - \hat{\tau}_{dis}\right)\right) \leqslant 0. \tag{14}$$

$\dot{V}$ is negative semi-definite for $\tilde{\tau}_{dis} \in R^n$. As $\dot{V}$ is negative definite it confirms the stability of the proposed controller.

Fig. 4 shows the design of the disturbance observer proposed for the tracking control. The difference between the control torque τ_{dis} and the estimated disturbance torque, $\hat{\tau}_{dis}$ is the actual torque which drives the system in the given trajectory compensating the disturbances.

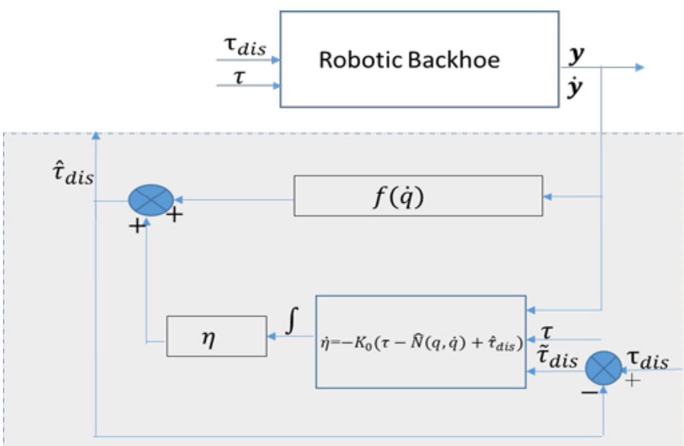


Fig. 4. Design of the proposed disturbance observer

4. Results and discussion

In this section, the validation of the proposed control with simulation and co-simulation experiments is performed. The parameters of the robotic backhoe used for the study are given in Table 2.

Table 2.

Parameters of the robotic backhoe used in study

Parameter	Value	Parameter	Value
Mass of boom, m_2	33.43 kg	Soil density	1.3 kg/m^3
Mass of stick, m_3	10.1 kg	Width of soil cut	60 cm
Mass of bucket, m_4	2.45 kg	Thickness of soil cut	40 cm
Link length boom, a_1	1.42 m	Pressure force of the bucket with soil, N	1 kgm/s^2
Link length stick, a_2	0.699 m	Coefficient of friction, μ	0.1
Link length bucket, a_3	0.55 m	Volume of bucket	0.66 m^3
Moment of inertia, boom	9.80 kgm^2	Acc” due to gravity, g	9.81 N/kg
Moment of inertia, bucket	2.432 kgm^2	Coefficient of resistance, ε	55,000 kg/(m^2/s^2)
Moment of inertia, stick	6.21 kgm^2	Penetration angle	30 deg

4.1. Simulation study

Simulation study in Matlab/Simulink package is performed to analyze the performance of the proposed control system during a digging operation. The reference trajectory the system has to follow is defined in Cartesian space, as shown in Fig. 5. As digging happens in the vertical plane, the dynamic model is reduced to a three DOF (boom, stick, and bucket) and the swing action is neglected. The simulation results with and without the proposed disturbance observer are compared in presence of the disturbance torque, as modelled in equation (3), against the desired

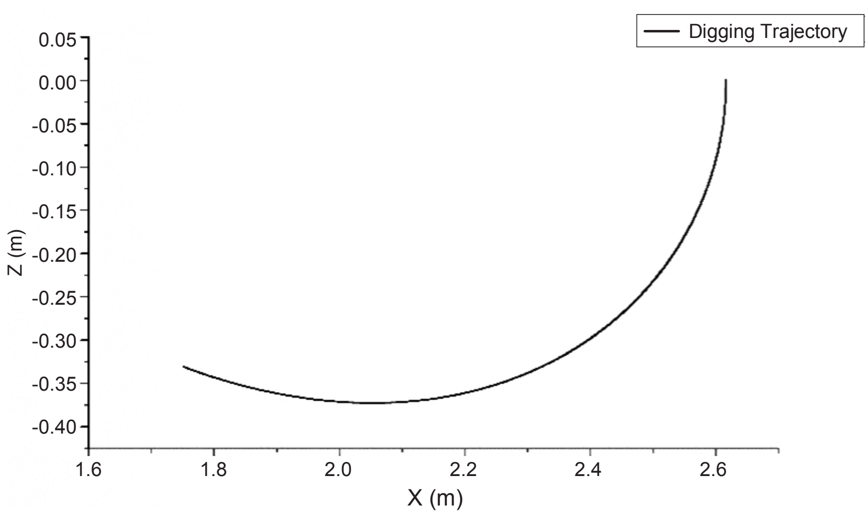


Fig. 5. Desired digging trajectory for the robotic backhoe

cut profile the bucket has to follow. As the bucket hits the ground, the system encounters the ground reaction torque in the opposite direction.

The gain values used for the simulation are $K_p = 100I$, $K_d = 20I$ and $K_0 = 2I$.

Fig. 6 shows the position tracking in the joint space followed by the three joints, boom, stick and bucket, respectively. Fig. 7 shows the position tracking error which is the distance between the actual joint positions and desired joint position in following the given cut profile.

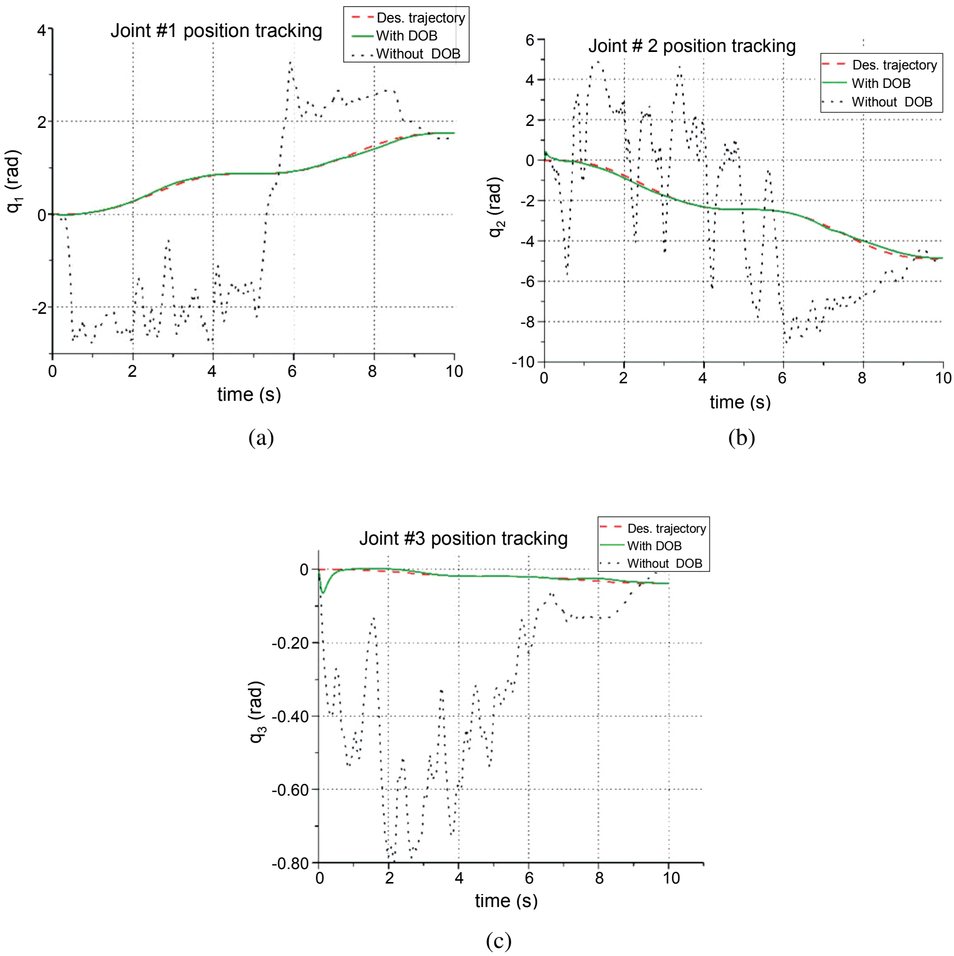


Fig. 6. Time profile. Position tracking time profile for the boom (a), stick (b), and bucket (c) joint in one dig cycle of operation

Fig. 8 shows the joint disturbance tracking in the joints followed by the three joints, boom, stick and bucket, respectively. The error in the estimation of joint disturbance torque for the three joints is shown in Fig. 9.

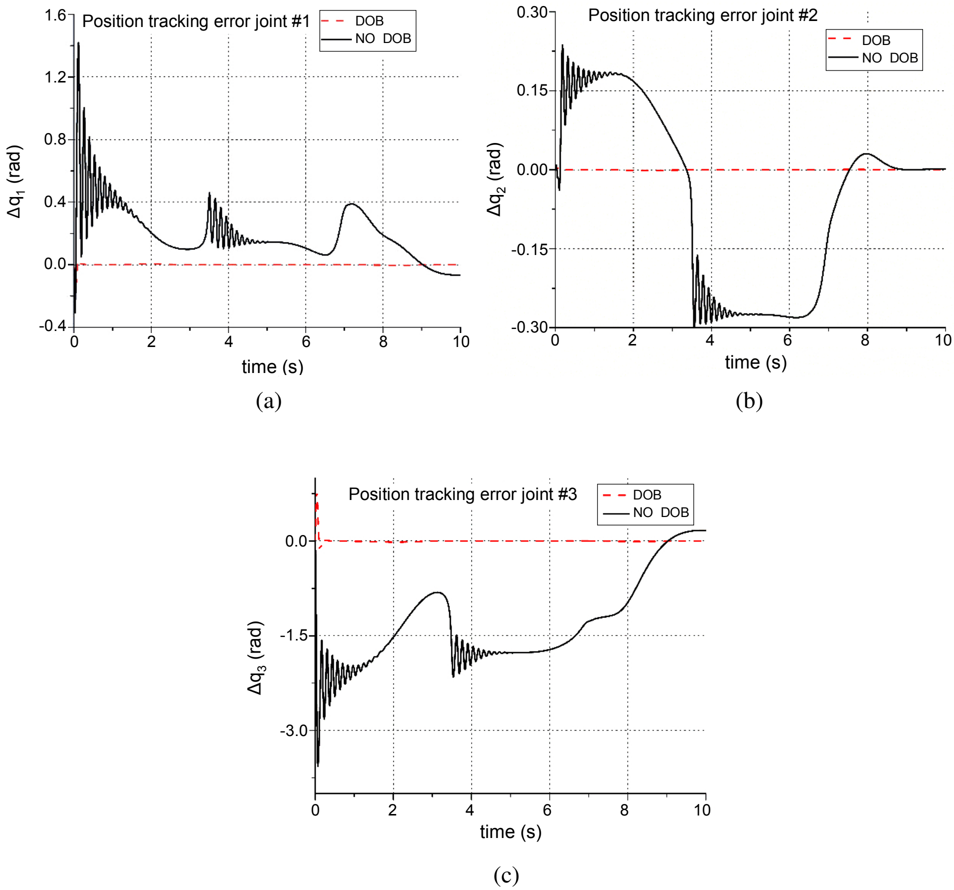
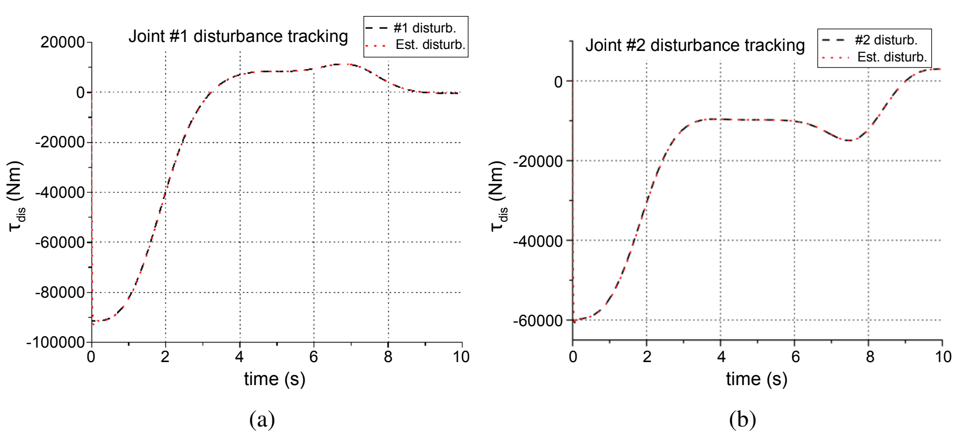
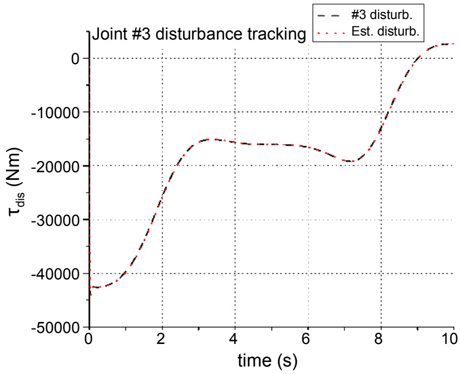


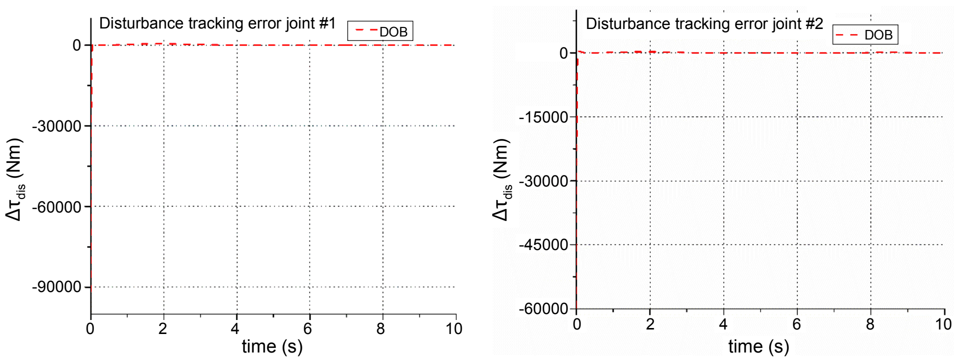
Fig. 7. Time profile. Position error time profile for the boom (a), stick (b), and bucket (c) joint in a digging cycle of the robotic backhoe



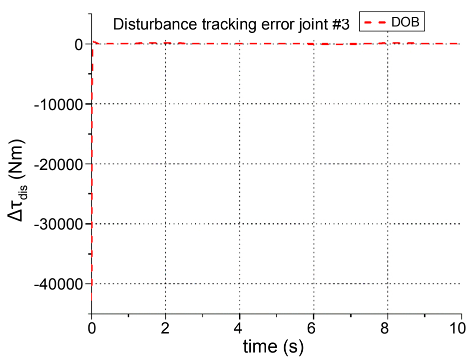


(c)

Fig. 8. Joint disturbance tracking time profile of the boom (a), stick (b), and bucket (c) joint of the robotic backhoe



(a) (b)

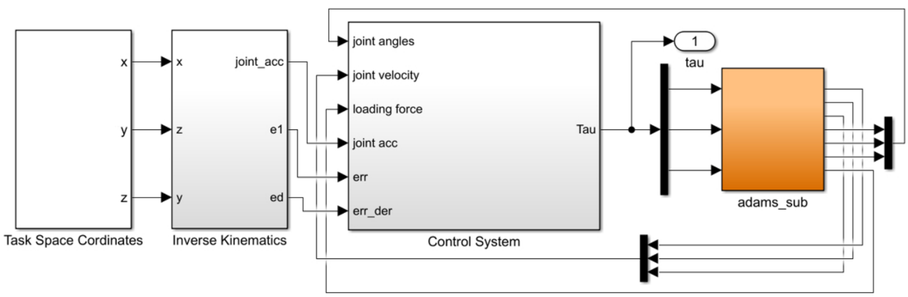


(c)

Fig. 9. Disturbance error time profile of boom (a), stick (b), and bucket (c) joint in the soil-contact task of a robotic backhoe

4.2. Experimental analysis

As this study focusses on the estimation of loading torque during digging, a validation based on co-simulation is performed on Adams/Matlab platform, as shown in Fig. 10. Co-simulation offers the advantage of validating the control system on the virtual prototype of the machinery and thereby reducing the dependency on hardware model to test the control algorithm [27]. A scaled-down CAD model of the system in a digging environment was imported to Adams and co-simulation was performed with a control algorithm developed in Matlab. The cycle of operation considered was to dig on a coarse sand environment and load the bucket.



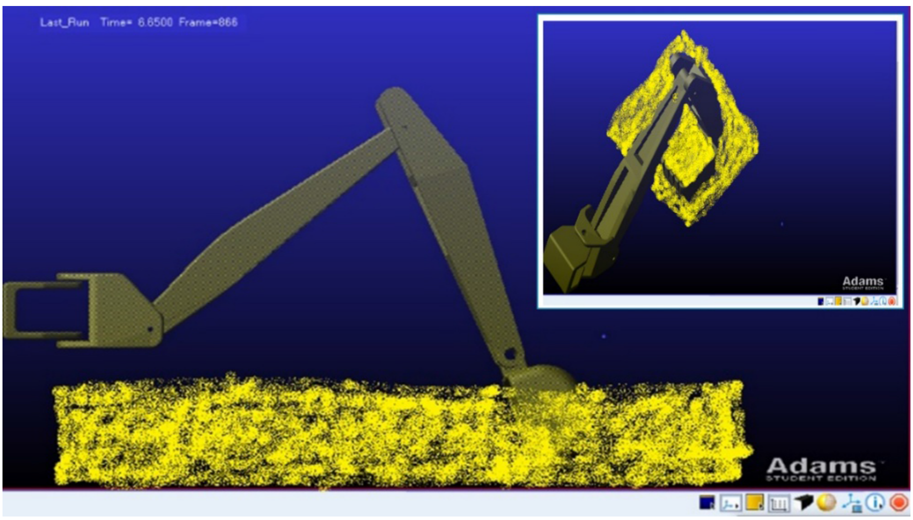
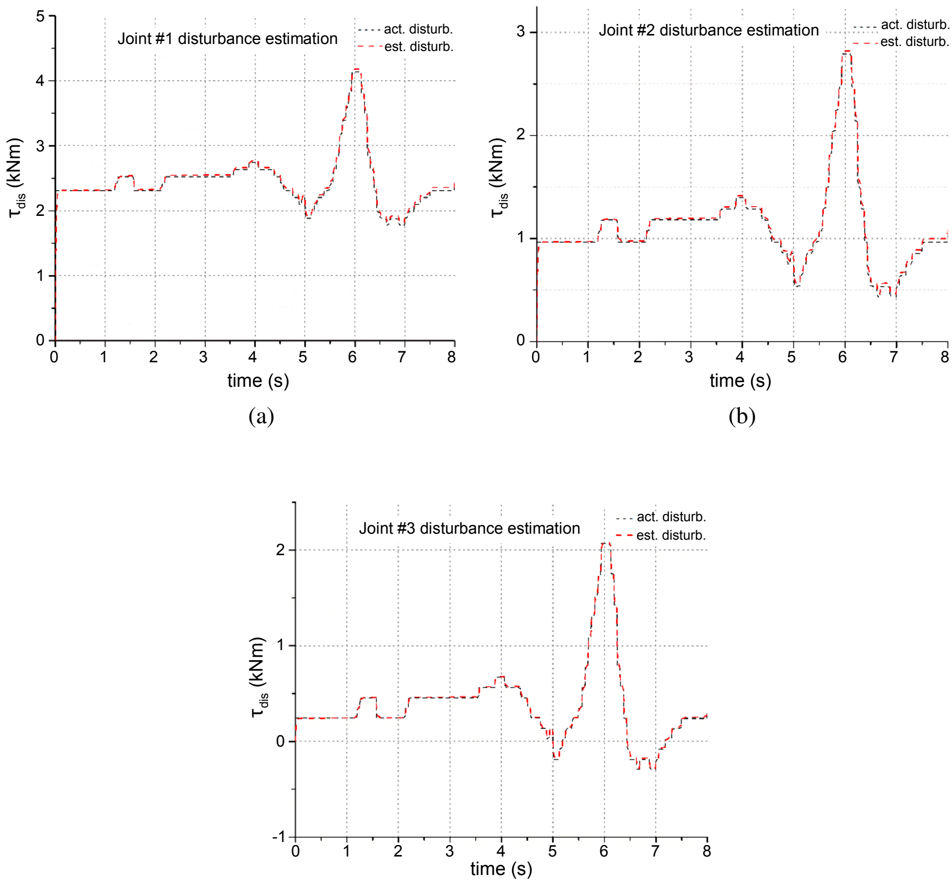


Fig. 10. Co-simulation experiment of robotic backhoe in MATLAB/ADAMS platform. The top image shows the model developed in Simulink. The bottom image shows the digging operation during co-simulation by the robotic backhoe

The system was required to follow a desired trajectory to scoop-up a bucket of sand, and the soil reaction force was modelled as in equation (5). Since, unloading operation is not considered, swing joint is held stationary. The estimation of the loading torques in the three joints for the entire cycle of operation are presented in Fig. 11. Experiments were performed by varying the gain, till the computed torque control with observer gave better performance. The selected gain values gave the least RMS error for simulation and co-simulation experiments. The chosen gains for the operation were $K_p = 2I$; $K_d = 0.5I$; $K_0 = 5I$.



(c)

Fig. 11. Loading torque estimation time profile of the boom (a), stick (b), and bucket (c) joint in the co-simulation experiment

The tracking of the joint trajectories for the constrained motion is shown in Fig. 12.

The performance of the control system is shown to be highly accurate. The results obtained verify the efficiency of the proposed control system in estimating the loading torque in autonomous operation of robotic backhoe in the context of

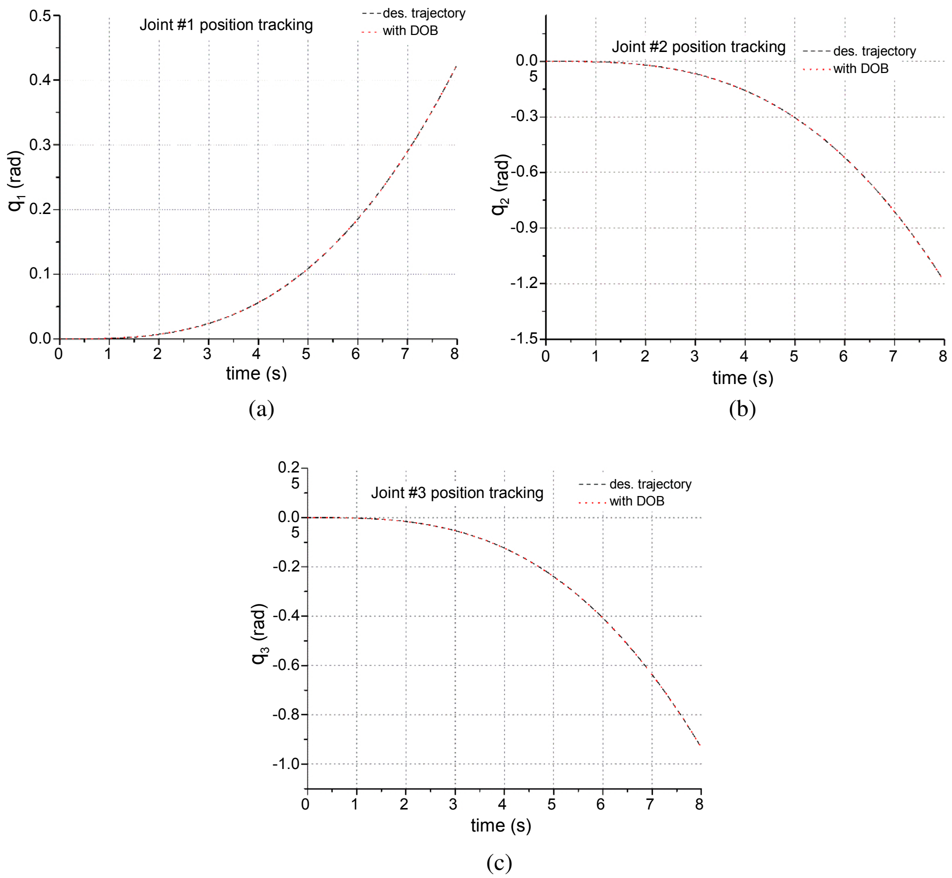


Fig. 12. Position tracking of boom (a), stick (b), and bucket (c) joint of the robotic backhoe in the co-simulation experiment

autonomous digging. The RMS error value for the position and disturbance tracking is given as,

$$Err\_q_{rms} = \sqrt{\sum_{i=1}^{n} \frac{(q_d - q_i)^2}{n}}, \tag{15}$$

$$Err\_\tau_{dis\_rms} = \sqrt{\sum_{i=1}^{n} \frac{(\tau_d - \tau_i)^2}{n}}. \tag{16}$$

Table 3 gives the RMS value of the tracking error computed for the robotic backhoe co-simulation based on the gain values in the co-simulation experiment.

The performance of the joint reaction estimation during digging through the proposed observer is validated through the simulation study.

Table 3.
RMS error. Position and disturbance tracking

RMS error	Joint #1	Joint #2	Joint #3
Trajectory tracking (rad)	0.1426	0.3424	0.2343
Disturbance tracking (N)	1.319	1.412	1.012

5. Conclusions

In this paper, we have proposed a disturbance observer-assisted control scheme as a solution towards the estimation of loading torque in the automation of robotic backhoe. The proposed observer estimates the reaction torque occurring during digging and provides a feed-forward compensation to suppress its effect in the autonomous operation of a robotic backhoe. For a given dig cycle of operations, simulations are performed to validate the performance of the control system. Furthermore, co-simulation experiment performed on a virtual prototype of the system on a bucket soil interaction task asserts the tracking efficiency of the control system. The results obtained demonstrate the feasibility of the control system in application towards enhancing the operator assistance in autonomous excavation and in novice training in virtual environment excavation task.

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