Proceedings

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Nicole Stephan · Roman Teutsch · Martin Thul *Hrsg.*

Commercial Vehicle Technology 2018

Proceedings of the 5th Commercial Vehicle Technology Symposium – CVT 2018

Springer Vieweg

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Editors

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Preface

Assisted, automated and autonomous driving and working is not only a current research topic, but also partially used in new products of the commercial vehicle industry. From this step, the industry expects above all a higher quality, more efficient workflows and an increase in the reliability and safety of the systems while simultaneously reducing costs. The 5^{th} International Commercial Vehicle Technology Symposium, which takes place from 13^{th} to 15^{th} of March, addresses different aspects of commercial vehicle development and production.

With regard to energy and resource efficiency, the topic of innovative drives with alternative fuels will be focused on. Another challenge is safety, reliability and durability, which is becoming more and more relevant as part of automation. Not only the improvement of the system components is important for innovative commercial vehicles, but also new concepts for their operation must be found to increase productivity. In order to improve the development and production process, it is furthermore important to use more and more powerful simulation methods and tools.

In relation to these topics, we are very proud that four high quality keynote speakers will present the state as well as future innovations in their main research and development areas. These include

- François Jaussi (Liebherr Machines Bulle SA)
- Christof Weber (Mercedes-Benz do Brasil)
- Stefan Stahlmecke (John Deere GmbH & Co. KG)
- Michael Fauser (StreetScooter GmbH)

This year's CVT Symposium is the 5^{th} in a series of very successful conferences, which took place every two years starting from 2010. With more than 200 participants, several demonstrations of commercial vehicles and more than 20 exhibitions from industry and research institutions, the symposium offers a wide variety of interesting aspects beside the oral and poster presentations. The oral presentations will take place in 2 parallel sessions. All the presentations in German language will be simultaneously translated into English for our foreign guests.

To guarantee a very high quality and a large impact, the program committee of the conference selected more than 50 very innovative contributions (talks and interactive poster presentations) out of all submitted papers. To ensure scientific innovation as well as practical benefit, at least 3 reviewers from academia and industry evaluated each submitted paper. In addition, the 40 best contributions are selected for this proceedings book.

We are also pleased to welcome two politicians of our state Rhineland-Palatinate, Prof. Dr. Konrad Wolf, Minister of Science, Higher Education and Culture, and Dr. Volker Wissing, Minister of Economic Affairs, Transportation, Agriculture and Viniculture, who will offer greetings of the state and open the dinner of the symposium.

Finally, we would like to take the opportunity to thank all people which were involved in organizing the CVT 2018 . In particular, we would like to thank our platinum sponsor Liebherr EMtec GmbH and Liebherr Component Technologies AG, all gold sponsors BPW Bergische Achsen KG, Daimler AG, John Deere GmbH & Co. KG, Volvo Construction Equipment Germany GmbH, BOMAG GmbH and Grammer AG, as well as the silver sponsor IAV GmbH Ingenieurgesellschaft Auto und Verkehr. Furthermore, we would like to thank the university board and the government of Rhineland-Palatinate for their kind support.

Prof. Dr. Karsten Berns
Speaker of the Center for Commercial Vehicle Technology
Kaiserslautern, March 2018

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Contents

Assisted and Automated Driving and Working

Energy and Resource Efficiency

Innovative Development and Manufacturing

Safety, Reliability and Durability

Simulation Methods

Assisted and Automated Driving and Working

Validation of an analytical method for payload estimation in excavators

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Abstract. In this proposed paper, a measurement based validation for a previously developed payload estimation method for excavators [1] is presented. The payload here refers to the weight exerted at the operating end (bucket) of the working attachment of an excavator due to the amount of material in the bucket. The proposed method employs an analytical approach, relying on calculating the payload as a function of the joint torques of the excavator working attachment. Since this approach requires the knowledge of the inertial parameters of the working attachment, a method to estimate these was proposed. The mass, center of mass and mass moment of inertia of each link are estimated recursively using simple motion trajectories of the working attachment. Once the inertial parameters are thus estimated, the payload can be estimated as a function of joint torques. Both these estimation methods were validated using measurements done on an 18 t hydraulic excavator. The paper discusses in detail the measurement runs performed for the validation, as well as the subsequent evaluation of the measurement data. Finally, the quality of the results is elaborated on, and suggestions for improvement of the accuracy and reproducibility of both estimation methods are presented.

Keywords: Driver Assistant Systems, Hydraulic Excavator, Payload Estimation.

1 Introduction

Small to medium size hydraulic excavators (operational mass of upto 30 t) are amongst the most commonly used mobile construction machines. Earth-moving and load-lifting operations constitute the majority of tasks performed by these machines (referred to as just 'excavators' henceforth). For both these operations, it is advantageous to know the value the mass of the material in the bucket. This knowledge is directly helpful for analyzing the dynamic stability of the machine,

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especially considering the fact that the dynamic motions of the robotic arm of the excavator can quickly lead to instability during motion. Furthermore, it can also be used for accurate loading of transport vehicles and thereby facilitate improved monitoring of mining sites.

2 Background

2.1 The hydraulic excavator

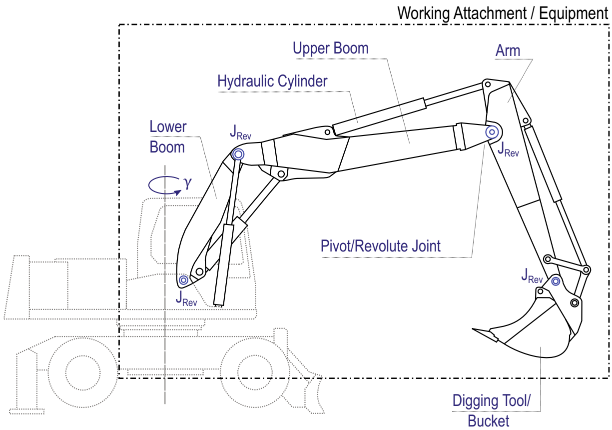


Fig. 1: Hydraulic excavator and its working attachment

A typical hydraulic excavator is shown in the fig. 1. The focus in this paper is restricted to the robotic arm of the excavator, also termed as the 'working attachment' or 'equipment'. This comprises the boom, the arm and a tool - which is a bucket in this case. The boom in the figure consists of two parts, with a revolute degree of freedom between the two. This configuration is termed as a two-piece boom. It is however also quite common to find a 'monoboom' construction, where the lower and the upper boom are one rigid component. The main advantage of the two-piece configuration is the compactness that it lends to the entire working attachment, especially when the excavator is to be transported from one site to another. The cylinder supporting the upper boom is then retracted during transport.

The entire working attachment is actuated using hydraulic cylinders, whose translational motion achieves rotational motion of the aforementioned components about the respective revolute joints (termed as J_{Rev} in the figure 1). Apart from these rotational degrees of freedom, the entire excavator is also capable of rotating about the vertical axis (superstructure rotation or slew motion, represented by γ in the fig. 1). Thus, for a two-piece boom construction as shown in figure 1, the working attachment can be considered to have 4 rotational degrees of freedom of the links, plus the slew rotational degree of freedom. The tool at the end of the working attachment is the means with which the excavator interacts with its environment. In this case it is the bucket, which combines the functions of digging and collection of material into one tool. The mass of the material contained in the bucket is termed as 'payload'.

2.2 Overview

The approach proposed in this paper builds upon the work of Ballaire and Müller [3]. In spite of its simple implementation, Ballaire's approach performs with a high degree of accuracy as was proven in the validation experiments carried out by Ballaire on a tractor front loader. The approach was modified to account for the additional degrees of freedom in the excavator working attachment. Furthermore, since Ballaire's approach also requires knowledge of the inertial parameters of the links involved, an approach for the required parameter estimation was also developed.

2.3 Proposed Method for Payload Estimation

The proposed approach implements a torque equilibrium about the revolute joints of the working attachment. The unknown payload is thereby determined as a function of these joint torques, with the assumption that the cylinder pressures (and the thus the motive forces) and accelerations can be measured and the inertial parameters be estimated. The following assumptions were made for the modified payload estimation method [1]:

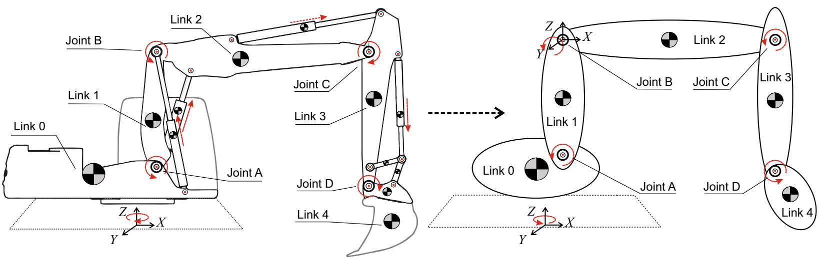


Fig. 2: Excavator working attachment: Simplified representation [2]

– Simplified geometry: The working attachment was condensed into 4 separate links connected with revolute joints, with the base link (lower boom)

mounted on a rigid body (superstructure) having a rotational degree of freedom about the Z axis.
- Constraints to relative motion: It is assumed that during the payload estimation, the upper boom will not move relative to the lower boom, and that the bucket will not move relative to the arm (in essence rendering joints B and D to be rigid during the payload estimation). Thus, during the estimation of payload, the working attachment can be considered to have 3 degrees of freedom.
- Effect of friction/damping: The total effect of friction and damping in the joints, the hydraulic cylinders etc. was considered under a lumped parameter for each joint, which is linearly dependent on the joint angular velocity.
- Location of center of gravity (CG) of payload: Since it is not viable to assume that the CG of the payload will be accurately known, all dynamic quantities pertaining to the payload CG are measured with respect to the arm-bucket joint. This assumption definitely leads to an error in the actual estimation, the effect of which is discussed in later sections.

When all relevant forces that play a role in the motion of the working attachment (and arise as a consequence thereof) are considered in establishing the torque equilibrium, the following equation can be obtained for the payload [4],[1]:

$$
\begin{aligned}
m_L = & \frac{M_A - M_{Damp,A} - M_C + M_{Damp,C} - m_1 g r_1 - m_2 g r_2 - m_3 g r_C}{g r_C + \ddot{z}_L r_C - \ddot{x}_L z_C + \omega_z^2 r_L z_C} \\
& + \frac{-m_{Buck} g r_C - m_3 \ddot{z}_3 r_C - m_{Buck} \ddot{z}_L r_C + m_3 \ddot{x}_3 z_C + m_{Buck} \ddot{x}_L z_C}{g r_C + \ddot{z}_L r_C - \ddot{x}_L z_C + \omega_z^2 r_L z_C} \\
& + \frac{-(J_1^S + m_1 s_{1A}^2)\ddot{\phi}_A - (J_2^S + m_2 s_{2A}^2)\ddot{\phi}_A - m_1 \omega_z^2 r_1 z_{S1}}{g r_C + \ddot{z}_L r_C - \ddot{x}_L z_C + \omega_z^2 r_L z_C} \\
& + \frac{-m_2 \omega_z^2 r_2 z_{S2} - m_3 \omega_z^2 r_3 z_C - m_{Buck} \omega_z^2 r_L z_C}{g r_C + \ddot{z}_L r_C - \ddot{x}_L z_C + \omega_z^2 r_L z_C}
\end{aligned} \tag{1}
$$

with:

M_N = Torque about N
m_k = Mass of component k
r_P = Horizontal distance of point P from the base of the lower boom
z_Q = Vertical distance of point Q from the base of the lower boom
$\ddot{x_k}$ = Translational acceleration of component k along the X axis
$\ddot{z_k}$ = Translational acceleration of component k along the Z axis
ω = Angular velocity of the working attachment about the Z axis
J_k^S = Mass moment of inertia of component k about its center of mass
s_{kN} = Distance from COM of component k and its preceding revolute joint N

As can be seen, the method requires the knowledge of the inertial parameters of the link, specifically the masses, centers of mass and the mass moments of inertia. Moreover, the representative joint damping is also unknown. The following section will describe a basic approach to estimate these unknowns.

2.4 Proposed Method for Parameter Estimation

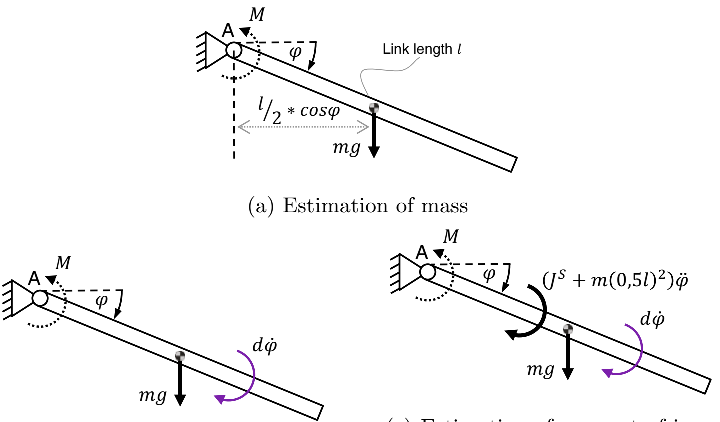
The inertial properties of a rigid body (i) in space can be described using 10 parameters: its mass, the center of mass relative to an inertial frame (i.e. 3 coordinates) and its moment of inertia which is represented by a 3x3 symmetric inertia matrix, which gives the following parameter vector:

$$p_i = [m_i, s_{x,i}, s_{y,i}, s_{z,i}, I_{xx,i}, I_{xy,i}, I_{xz,i}, I_{yy,i}, I_{yz,i}, I_{zz,i}] \tag{2}$$

Assuming for a serial kinematic chain that there are suitable sensors which can measure the joint velocities and accelerations (at each joint), the inertial parameters for each link of this mechanism can be estimated as follows [5]:

1. The Newton-Euler equations of motion are established and formulated in such a way that there exists a linear dependence of inertial parameters
2. The parameters are then estimated using approximation algorithms such as the least-squares method

All inertial parameters can be estimated only if all components of joint torque/force are measurable. However, owing to the restricted degrees of freedom at each joint, this is not possible. Thus some parameters can only be estimated in linear combinations, while some - especially those concerning the links near the base - are not estimable at all. For detailed analyses, refer to [6],[7],[8],[9],[10]. Considering that for the proposed payload estimation approach only a limited



(a) Estimation of mass

(b) Estimation of joint damping

(c) Estimation of moment of inertia

Fig. 3: Link parameter estimation: Free body diagrams [1]

number of inertial parameters are required, a much more simple approach was adopted wherein all parameters were estimated as a function of the relevant joint torque. [1] Thus, in a first step for a static case, the link joint torque will comprise only of the static weight of the link, i.e. the link mass and its center of mass (refer fig. 3a).

In the next step for the case where the joint rotational velocity can be considered constant (negligible angular acceleration), the joint torque will be comprised of the torque due to the link static weight and a damping dependent counter torque. Assuming the effective damping torque as a linear function of the angular velocity, this will lead to the corresponding damping constant (refer fig. 3b).

Finally, in the third step, for a constant link joint angular acceleration, the only unknown term in the torque equation will be the mass moment of inertia of the link (refer fig. 3c). In each step, the estimation starts from the link furthest to the base joint (i.e. the arm in this case), and follows recursively to the base link (i.e the lower boom)

It is worth noting here, that the center of mass of the links illustrated in the fig. 3 is assumed to be at the geometric center of the link. The mass is estimated as a function of joint torque, or in other words, the torque contribution of just the mass of the link is actually a linear combination of the mass and the center of mass. This linear combination appears unchanged in the payload estimation equation (eq. 1). Thus, since the torque contributed by the actual weight of the link and not the individual value of the mass itself is considered, the error contributed by the assumption of the position of the center of mass is compensated for. This is handled in more detail in [1].

Both the proposed methods were verified using a multi-body simulation of an rigid body model of an excavator. The results show that the inaccuracies in the parameter estimation are well compensated for in the payload estimation approach, as can be seen in the fig. 4. In fact the deviations in estimation only arise from the lack of knowledge of the actual payload center of mass, which leads to erroneous calculation of the payload accelerations.

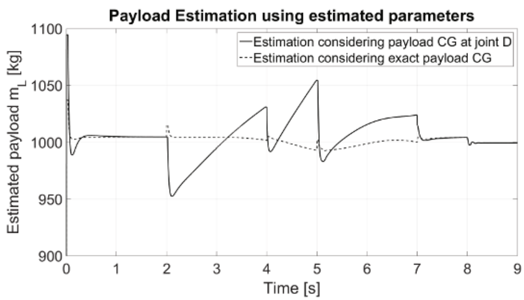


Fig. 4: Payload estimation using estimated parameters (MBS simulation); actual value of payload = 1000 kg [4],[1]

3 Validation

3.1 Measurement Setup

The proposed methods were validated using measurements on an 18 t excavator with a two-piece boom configuration. The total sensor data available is depicted in the table 1. Along with the measurement data gathered, pertinent data relating to the kinematics of the working attachment (link lengths, angular distances between fixed joints etc.) was measured as well. This was later put to use to calculate the joint angles from the measured stroke values and consequently the joint torques.

Table 1: Sensor data available on test excavator

Sensor type	Sensor position	Unit	Purpose
Pressure	Lower boom cylinder	bar	Determine joint torque M_A
Pressure	Arm cylinder	bar	Determine joint torque M_C
Pressure	Bucket cylinder	bar	Determine joint torque M_{Buck}
Cylinder stroke	Lower boom cylinder	mm	Joint angle J_A
Cylinder stroke	Arm cylinder	mm	Joint angle J_C
Cylinder stroke	Bucket cylinder	mm	Joint angle J_D
Slew angle	Superstructure	$^\circ$	Yaw velocity of the excavator
Acceleration ($\ddot{x}$, $\ddot{z}$)	Center of mass of arm	m/s^2	Acceleration of arm
Acceleration ($\ddot{x}$, $\ddot{z}$)	Next to bucket joint	m/s^2	Acceleration of bucket/payload
Angular position	Superstructure	$^\circ$	Roll and pitch of the excavator

It must be mentioned, that there was no data available for the upper boom cylinder: neither the cylinder strokes nor the cylinder pressures could be determined. As noted previously, this cylinder is not actuated at all during normal excavator operation. However, data pertaining to the motion of the upper boom is required for estimating its inertial parameters. Considering the dimensional similarity between the upper boom and the arm, it was assumed that the inertial parameters of the upper boom do not vary considerably from those of th arm (which are estimable). This naturally contributes to an error in the later steps, as discussed in the final section. In interest of data synchronization, along with the aforementioned sensor data, a voltage signal was also logged. At the beginning and end of each measurement run a DC voltage source triggered this signal. The trigger points were used in the subsequent data evalation to synchronize all signals on a common time axis.

The measurements were divided into two parts. The first part concerned itself with parameter estimation. During these set of measurements, the bucket was removed from the working attachment. This left the working attachment with three links, namely the lower boom, the upper boom and the arm. The second part of the measurements comprised different runs concerning payload estimation. Here, the excavator performed motions with different trajectories with buckets of different known masses i.e. different known payloads.

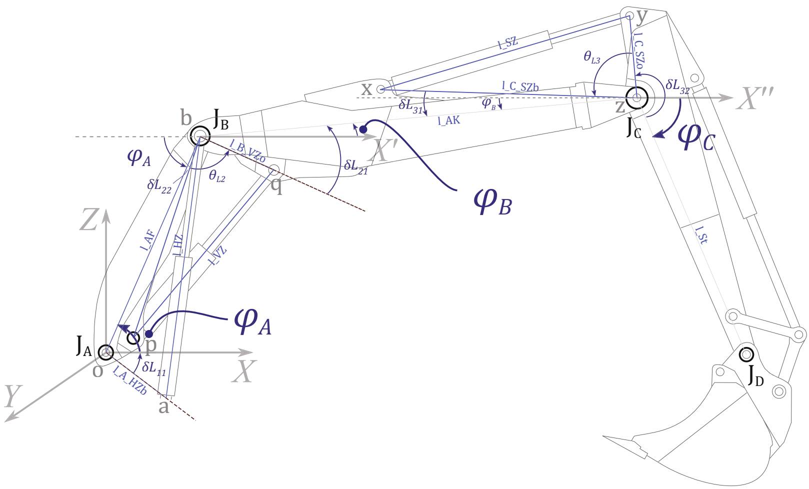
3.2 Measurement Data Evaluation

The evaluation was done using the basic functionalities offered by the open source libraries NumPy, SciPy and Pandas in the Python programming language. The programming environments used were Jupyter Notebook and Spyder (Scientific PYthon Development EnviRonment).

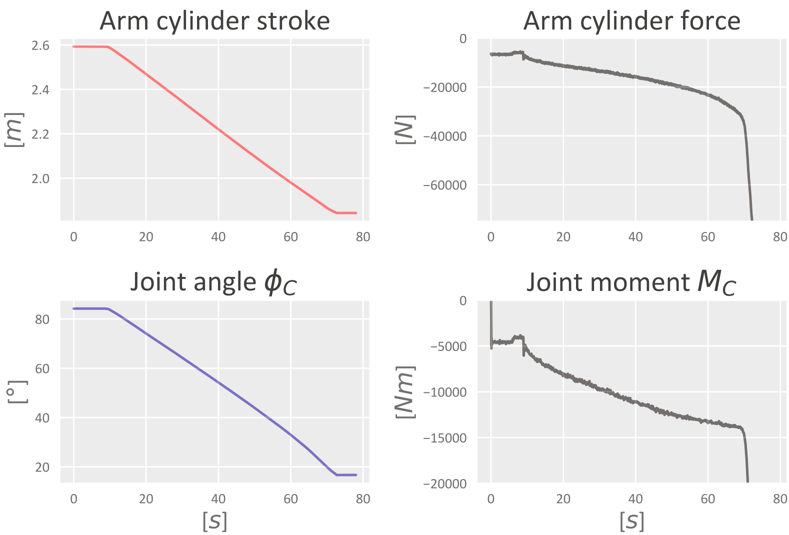
As has already been mentioned, both the proposed methods basically involve establishing a torque equilibrium about a revolute joint. In order to determine the joint torques however, it was first necessary to evaluate the joint angles, which are a function of the cylinder strokes. Each joint angle can be calculated using the cosine rule - the variable side of the relevant triangle being the cylinder stroke, with the other two sides being geometric constants (see fig. 5a). Thus, the time based signal of cylinder strokes can be converted to obtain a time based signal of joint angles. The fig. 5b illustrates this for the case when only the arm cylinder was actuated with all preceding links (lower and upper boom) stationary. An extension of the arm cylinder decreases the calculated joint angle (ϕ_C), which is reasonable when the interpretation of ϕ_C as shown in fig. 5a is considered. The fig. 5b shows further the behavior of the cylinder force and the corresponding joint torque required achieve this motion. As mentioned previously, the cylinder forces were calculated from the cylinder pressure values. The torque was calculated by considering the lever of the active component of this force about the relevant joint.

Determination of Link Mass The measurement results pertaining to the estimation of the mass of the arm is shown in fig. 6. For a static position of the working attachment ($\phi_C = 43.89°$), a relatively constant joint torque is obtained, as is expected. The mass estimation was done for several different angular positions of the links. In the evaluation of the second part of the measurements, the mean value of these estimated masses was considered.

Determination of Joint Damping For the assumption regarding an equivalent joint torque linearly dependent on the damping to hold true, it is important to estimate the damping for a constant angular velocity of the joint. The measurement data shows, that even though the joint angular velocity doesn't remain constant over the entire span of the relevant measurement run, there are certainly some sections where the behavior of the velocity remains constant and as such are relevant for the estimation of the damping constant. In order to avoid the inflated estimation results the damping constant was estimated for a section of the data where the angular velocity value was not very close to zero (fig. 7).



(a) Excavator kinematics



(b) Extension of arm cylinder

Fig. 5: Determination of joint angles and joint torque from measurement data

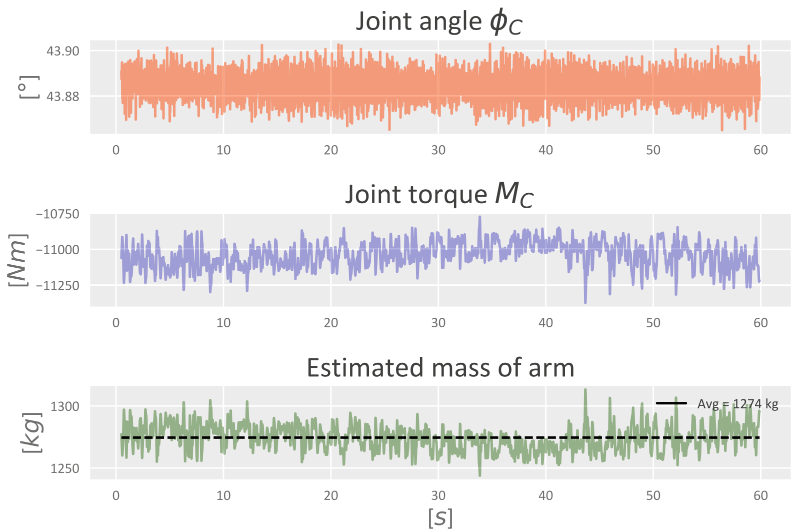


Fig. 6: Measurement data evaluation: Estimation of link mass (Arm)

Determination of Link Mass Moment of Inertia With parameter values determined in the previous estimation runs, the mass moments were inertia were determined for trajectories with constant angular acceleration. For reasons mentioned in the previous section, only those sections of the measurement data which exhibited with angular accelerations not very close to zero were considered. Mean values of parameters estimated over several measurement runs are summarized in the table 2. These values were later used to estimate the unknown payload.

Determination of an unknown payload The measurement runs dedicated to payload estimation involved buckets of different, known masses and two different trajectories for each payload. The first trajectory involved simultaneous actuation of the arm and lower boom cylinders (thereby giving simultaneous actuation of the joints J_A and J_C) and slew motion i.e. rotation of the entire working attachment about the vertical axis. With all joint motions occuring together, all dynamic effects come into play. The second trajectory consisted of a similar, simultaneous actuation of J_A, J_C and slew motion, but the actuations performed in such a way so as to mimic a usual digging cycle. Since the evaluation of the measurement data is still ongoing, the results of only the first run of payload estimation are discussed here.

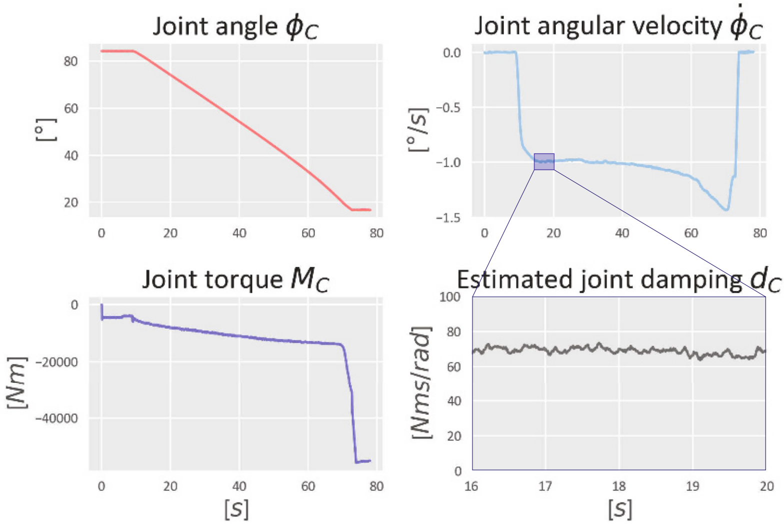


Fig. 7

Table 2: Estimated parameters (mean values)

Parameter	Link/Joint	Estimated value	Unit
Mass	Lower boom	1610	kg
Mass	Upper boom	1610	kg
Mass	Arm	3456	kg
Damping	Joint A	44.25	Nms/rad
Damping	Joint C	$2.535e04$	Nms/rad
Moment of Inertia	Lower boom	$-1.99e+04$	$kg \cdot m^2$
Moment of Inertia	Upper boom	$-1.99e+04$	$kg \cdot m^2$
Moment of Inertia	Arm	$9.65e+04$	$kg \cdot m^2$

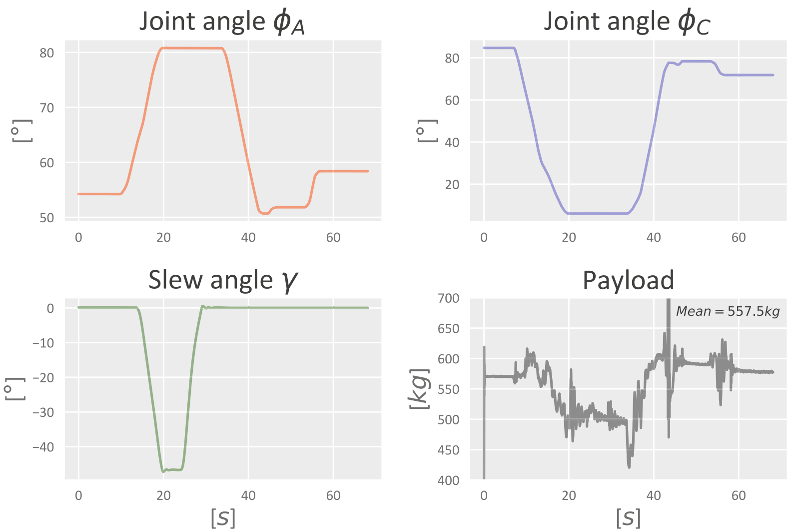


Fig. 8: Estimation of unknown payload (actual value 544 kg)

The results for payload estimation with the first trajectory can be seen in the fig. 8. If the mean estimated payload is considered, a relative error of around 2.5 % is obtained for the actual payload value of 544 kg. However, there is considerable fluctuation in the behavior of the estimated payload, which means that the dynamic effects were not been entirely compensated for. In fact, if the behaviors of the angular accelerations are analyzed, it can be seen that the fluctuations seen in the joint angular accelerations are reflected directly in the estimated value of the payload (fig. 9).

4 Discussion

The results in the previous section show that in spite of the assumptions made in developing the approaches for parameter and payload estimation and significant missing information, mean relative error remained under 5 % - or an estimation accuracy of above 95 %. Especially if the simplicity of both approaches is considered, then this is a very promising result for the developed approaches.

Based on this it can be concluded that if the payload is to be estimated in order to monitor how much material is being transported, then the approach even in the current state is quite promising. It is however quite unsuitable at this stage as an input to further analyze the stability of the machine. For instance, the lack of compensation of dynamic effects would substantially compromise

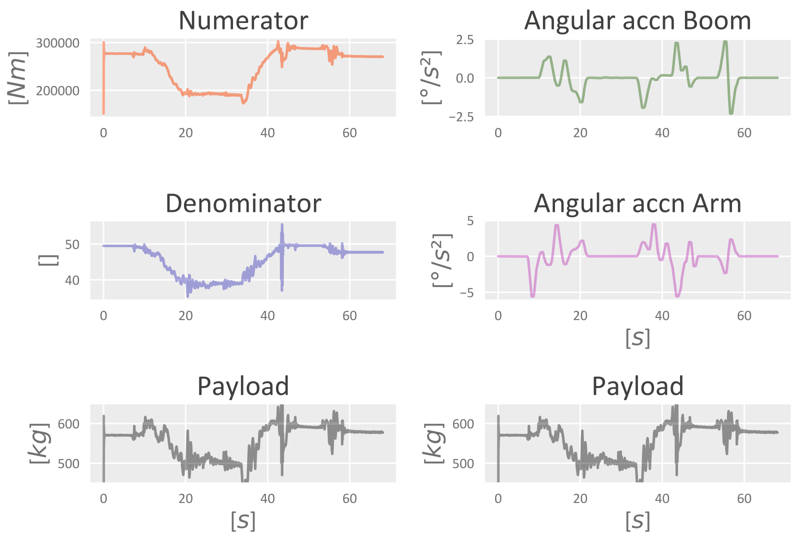


Fig. 9: Fluctuations in estimation of payload (actual value 544 kg)

the effectiveness of the stability estimation since the local fluctuations in the estimation cannot be ignored.

There are a few aspects inherent to the approaches themselves which need to be improved upon. As previously discussed, the calculation of the angular accelerations of the joints poses a significant challenge, especially since there are multiple differentiation steps involved: from the available translational cylinder strokes to the required joint angular accelerations. The angular acceleration values are also involved in the estimation of the link moment of inertia, making it quite likely that the error inherent in the accelerations also contributes to the estimation of the moments of inertia.

The assumed inertial parameters of the upper boom also pose a source of error. Estimations regarding inertial parameters in general could also be supplemented by studying the geometry of links. A study of excavators up to 30 t available in the market reveals that there is not significant difference in link geometries, even when machines of different manufacturers are considered. For instance, the shape and the location of the arm joint remains more or less the same for different machines. Preceding works have shown [4], that the location of the center of mass for instance can be quite accurately predicted with such geometry based approaches. The information gleaned from such an approach could be used in combination with the existing parameter estimation approach to improve the overall estimation accuracy. Another aspect is the assumption that the damping torque is linearly dependent on the angular velocity. Hydraulic cylinders exhibit stick-slip effects, which is why treating the damping behavior more like a Stribeck curve for instance would perhaps offer some improvement in the estimation of damping behavior.

As mentioned in the earlier section, the evaluation of the measurement data is still ongoing. Currently, apart from the improvements proposed above, different machine learning approaches are being implemented with an aim to achieve a more robust estimation of unknown parameters. With an improved estimation of the inertial parameters and more accurate calculation of the accelerations, it can be expected that the dynamic fluctuations in the payload estimation would decrease in subsequent evaluations.

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Benchmark of Different Calibration Methods of Driver Assistance Systems (DAS) Sensors at the End of Line of a Truck Final Assembly Plant by a Tolerance Chain Analysis

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Abstract. For the proper function of modern Driver Assistance Systems, all related sensors need to be calibrated to the coordinate system of the truck. Today, several different systems for such calibration operation are available on the market to perform the calibration in the End of Line area of a truck final assembly plant. This benchmark compares three different systems under the condition that the process for positioning of calibration targets related to the driving direction of trucks is capable (*cpk* > 1.33). A tolerance chain analysis of the positioning systems has been made to determine the related capability of each system. For the process of measuring the driving direction of a truck, several measurements have been made with each system.

Keywords: End of Line, sensor calibration, Driver Assistance Systems, product testing.

1 Calibration of Driver Assistance System Sensors

Modern sensors of Driver Assistance Systems (DAS) like camera, radar or LiDAR require an initial alignment of their coordinate system to the coordinate system of the truck. This alignment (calibration) in regard to the coordinate system of the truck is mandatory for the proper function for object detecting especially for long distance applications like Adaptive Cruise Control (ACC) or Lane Departure Warning (LDW) which are the “eyes” of the future Autonomous Driving.

The calibration is performed in the End of Line (EoL) area of a truck final assembly plant and requires equipment for a reliable and precise measurement of the wheel geometry of the truck as well as the positioning of the calibration targets in relation to the driving direction of the truck. A high performance in accuracy and reproducibility of the test stand is necessary to align the DAS sensors in a range of some angular minutes (smallest specified tolerance: ±3 angular minutes) in regard to the coordinate system of the truck (see Fig. 1 and table 1).

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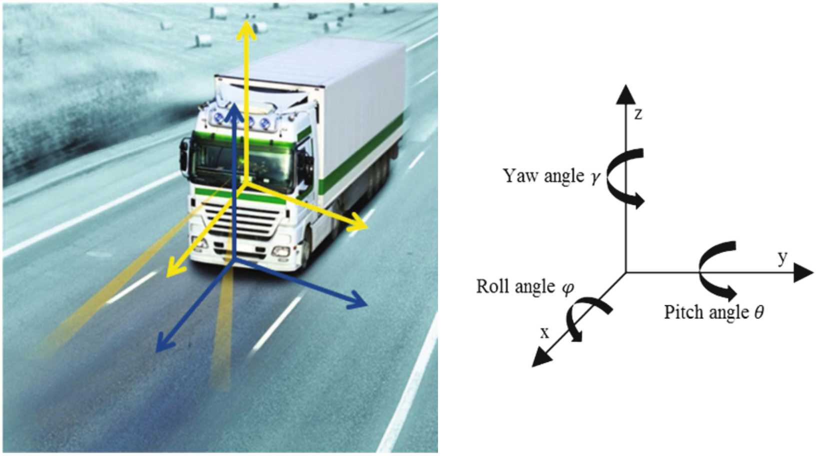

Fig. 1. Left: Different coordinate systems for cameras (LDW); yellow = camera coordinate system; blue = vehicle coordinate system
Right: definition of the coordinate system

Table 1. Tolerance values of requirements for calibration of camera based Driver Assistance Systems with a target

Max. angle error	Roll/Pitch/Yaw	±0.05° (±3')
Max. position error	X-position	±20mm
	Y- and Z-position	±2mm