Towards Optimal Force Distribution for Walking Excavators

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Abstract—This paper presents the successful implementation of force control strategies on a 12 ton walking excavator to optimize the ground reaction force distribution for better stability, less terrain damage and to reduce the operation complexity. Using cleverly arrange standard industrial valve components to separately control in- and out-flow of the hydraulic cylinders, we achieve accurate and fast joint torque control purely based on pressure feedback. On the full system level, we realize an automated force distribution to adjust the center of pressure and to level out the cabin of the machine. While the operator has still full control over the excavator, this assistance system guarantees permanent ground contact and ideal force distribution among the all four wheels independent of the level of the terrain. The proposed method significantly improves operability of the walking excavator in rough terrain.

I. INTRODUCTION

Walking excavators [1] belong to some of the most versatile but at the same time most complex mobile construction site machines. They are deployed in all kinds of special scenarios that require advanced mobility such as in the mountains, in rivers, or other hardly accessible areas. In contrast to traditional tracked vehicles, the newest generation of multi-purpose excavators developed by Menzi Muck AG (e.g. M545 depicted in Fig. 1) is equipped with four legs that each have three degrees of freedom and an actuated wheel.Thanks to this setup, these 12 ton construction site machines are able to drive or walk over challenging terrain.

However, for all locomotion maneuvers, the human operator must manually synchronize the motion of the four legs, meaning that he has to manually control the valve of each of the three cylinders per leg. This coordinatively challenging work requires very skilled machinists, particularly when moving forward and excavating at the same time. Moreover, the permanent coordination necessary to move the machine over bumpy terrain can be very exhausting.

One of the main problems with four legs in simultaneous ground contact is that a stiff and position controlled system like the M545 tends to be unstable in the sense that it can be permanently wiggling over the diagonal axis of contact if the elevation of the terrain changes. Moreover,

if the center of gravity (CoG) is close to the geometric center of the contact points, almost the entire weight of the machine is supported by one diagonal axis. This implies high peak forces which can damage the terrain or wear off the suspension system of the excavator. The typical approach to overcome this deficiency in wheeled vehicles is the use of passive suspension systems (e.g. [2]) that can lead to significantly improved climbing capabilities. Such mechanical intelligence is often applied in the field of rover type systems. In hydraulics, a common concept is the application of a swing axle at the front or the rear suspension [1]. Unfortunately, all these passive suspension systems limit the versatility of the machines.

The goal of this collaborative project between the Autonomous Systems Lab of ETH Zurich and Menzi Muck AG was to implement an active contact force adaptation on a walking excavator to path the road for autonomous operation respectively locomotion of such vehicles in challenging environments. Enhancing the mobility of machines using active suspension systems is applied in the walking community since the very first developments [3]. Most of the large scale legged robots used for forestry work (e.g. Timberjack Hexapod Robot), to work in hazardous environments (e.g. Mantis Robot [4] or TITAN XI [5]), or for demining (e.g. COMET-VI [6], [7]) use some sort of force, respectively impedance control to adapt to the ground. Today, the most advanced four legged robots, such as the hydraulic quadrupeds BigDog [8] or HyQ [9], or the electrically actuated systems StarLET [10] or MIT Cheetah [11] are fully force controlled. This enables these robots to actively regulate their (dynamic) behavior by precisely modulating the ground reaction forces.
Taking inspiration from the underlying control techniques, which are often based on some sort of virtual model control [12], the present paper outlines a method to implement active contact force adaptation for a walking excavator using existing industrial components paired with advanced control algorithms. On an instrumented testbench, we first developed a force control strategy for the individual cylinders based on pressure feedback. The characteristics and performance of our approach using industrial components are compared with some of the most advanced hydraulic robots that are used in research [9] as well as with the highest performant hydraulic valves that could be found on market. Based on this local control approach, we then successfully implemented an overall force distribution algorithm to adjust the center of pressure as well as to level out the operator cabin. The proposed algorithms were tested on a full-scale Menzi Muck M545 respectively an A91 with the same chassis.

**II. FORCE CONTROL OF A HYDRAULIC CYLINDER**

Key element to an optimal ground contact force distribution is precise cylinder force control [13]. However, in contrast to some of the best hydraulic walking robots (e.g. [9]), economic reasons and system robustness inhibit the use of additional force sensors (Fig. 2). In fact, force control must be achieved solely based on pressure readings ($f_h$) and hence requires to estimate the load force $f_l$ respectively friction force $f_f$ based on state (piston position $x_p$, piston velocity $\dot{x}_p$, and pressure $P$) feedback. Furthermore, standard valves that are in use in construction site machines typically show very different characteristics compared to walking robots like HyQ [9], BigDog [8], or Atlas [14]. Hence, the first big challenge was to achieve accurate and fast-enough force control using standard components.

**A. Test Bench Setup**

To characterize the force control behavior and to tune controllers, we developed a single axis test bench (Fig. 3) consisting of an active cylinder with pressure sensors (Rexroth RE 95138), a load cell to measure the output force (MecSense PC4), a passive cylinder to produce the counter force, an incremental position sensor (Micro-Epsilon WPS-2100-MK77) to measure position and correspondingly flow, as well as a standard proportional valve (Duplomatic BLS6).

**B. Friction Identification and Modeling**

To accurately control the mechanical force ($f_l$) based on pressure readings in the chambers, a good friction model is required. For small scale cylinders which are typically used in systems like HyQ (cross section area $A = 2.01 \cdot 10^{-4}$ m$^2$, maximal hydraulic force $F_{max} = 3$ kN), the friction properties show a quite complex behavior dominated by static and dynamic effects. As show in Fig. 4(a) (red), the friction has highly-nonlinear and dynamic properties. As shown in [15], the underlying effects can only be captured by a relatively complex LuGre model [16] respectively the models developed by Tran et al. [17] which includes 23 parameters that must be estimated.

In contrast thereto, the large scale cylinder employed in the M545 ($A = 7.85 \cdot 10^{-3}$ m$^2$, $F_{max} = 200$ kN) shows much smaller relative friction with very limited dry friction of less than 1% of the maximal force (blue). The corresponding characteristics can be accurately captured by a simple Stribeck curve [18] as depicted in Fig. 4(b). The frictional effects seem significantly less important than what has been reported in other studies like [19], [20] and in contrast to other solutions implemented in excavators [21], accurate force control seems possible without an additional load cell.

**C. Valve Setup and Control**

Today’s most advanced hydraulic robotic systems like HyQ, BigDog, or Atlas are actuated by some of the highest-performance valves that can be found on market, e.g. Moog E24 respectively E30, which feature extremely high control bandwidth (> 200 Hz) at very low weight. This is achieved by high-precision manufacturing such that the no-flow position in the middle configuration of the valve (red box in Fig. 5) reduces to a single point (critically closed valve).
In contrast thereto, standard valves of construction site machines often have a closed center spool with large overlaps. For example, the Duplomatic valve used in our test excavator features an overlap of almost 50%. This is an easy and inexpensive way to minimize the flow through the valve when it is closed. However, when controlling the valve in pressure mode and hence around zero flow, this overlap can be compensated but has to be crossed each time the measured signal crosses its reference. Beside energetic inefficiency, the overlap leads to a deadband, which significantly decreases the controller performance.

To overcome this problem using standard components, the valve can be split in two independently controlled sections which are connected to the same cylinder in parallel (Fig. 5, yellow background). Thereby, in- and out-flow of both chambers can be independently controlled and the over- respectively underlap of the valve setup (i.e. its "closed"-position) can be electronically set such that the valves are critically closed.

D. Performance Evaluation

We compared the performance of (A) the standard valve of the M545, (B) the standard valve in double configuration, and (C) a similar-sized valve with the highest performance we could find on the market (Moog G671). For this comparison, only the hydraulic force control loop was considered (no friction compensation as outlined in Sec. II-B). For pressure regulation, we implemented a simple PI controller:

$$u_v = PI(\Delta p).$$

The external mobile pump of 4 kW electric power was operated at constant pressure of 200 bars, which corresponds to an average pressure level we expect in the excavator. The houses between the pump and valve as well as between the valve and cylinders were selected to have about the length and diameter as in the M545.

The performance comparison in the step answer (Fig. 6) and the sine following (Fig. 7) indicates that the single valve has already significant errors at 5 Hz and loses track entirely at 10 Hz. The performance estimation resulted in a bandwidth of about 5 Hz for the standard valve, about 15 Hz for the double configuration and about 25 Hz for the Moog valve. Beside bandwidth, the double configuration convinces due to a good performance around zero flow.

III. PROTOTYPE IMPLEMENTATION ON M545

The control system for the prototype system is implemented on a National Instrument’s compactRIO (cRIO) system (Fig. 8). This real time processor and FPGA unit features the hydraulic force control loops for each cylinder as well as the high-level force distribution and inclination controller. The cRIO is connected to the system’s CAN bus that allows to read user Joystick signals as well as joint sensor measurements. Using the serial USB interface, a myAHRS+ IMU with integrated Kalman filter provides information about the cabin orientation (roll and pitch) and its acceleration. For cylinder control, we read in analog pressure signals of both chambers A and B and provide current command signal to the valve using standard DC motor control units.
IV. EXCAVATOR KINEMATICS

The kinematics of a single leg $j \in [1..4]$ of the M545 (Fig. 1) can be described by the 3 actuated joints $\varphi_j$ and a set of link lengths $\xi_j$. With these parameters, the contact point can be generally expressed in a body fixed frame $B$ as

$$b_r_j = b_r_j (\varphi_j, \xi_j)$$

with the corresponding Jacobian

$$b_J_j = \frac{\partial b_r_j (\varphi_j, \xi_j)}{\partial \varphi_j}.$$  \hfill (2)

In the static case and for a given contact force $bF_j$ at the wheel, we can calculate the torques for the three joints using Jacobi-transposed mapping

$$\tau_j = bJ_J_j' bF_j - \sum_i bJ_J_i' bG_i.$$

The second part corresponds to the gravitational contribution of all segment masses of the leg links (see [22], chapter 5.1). Given the joint torques, a simple trigonometric mapping yields the individual cylinder forces.

In regular operation, the wheel has significantly less traction force (tangential force) than normal force ($F_{j,z} >> F_{j,x}$) and since the roll angle of the chassis is relatively small, the torque for the three joints can be approximated by

$$\tau_j \approx \frac{\partial b_r_j}{\partial \varphi_j}^T F_{j,s} \quad \hfill (5)$$

$$F_{j,s} = t F_{j,z} - tG,$$

with $tG$ corresponding to the equivalent mass of the leg (including wheel) pressing on the ground. According to the datasheets of Menzi Muck and [23], the supporting mass is about 940 kg. In the following, we will refer to $F_s$ as support force of the chassis. In case $F_{j,s}$ becomes negative, leg $j$ is not supporting the chassis but is pulling it to the ground.

V. GROUND CONTACT FORCE CONTROL

This section investigates how accurately the ground contact force can be adjusted with the fully instrumented M545.

In a first experiment, we placed an industrial balance underneath the right hind leg while continuously increasing the desired support force $F_{s,des}$ from 0 to 35 kN. As depicted in Fig. 9, the ground reaction force estimated from pressure readings aligns very well with the balance measurements (linear regression coefficient of $R^2 > 0.99$). With a maximal measurement error of $<1.3 \text{kN}$, we achieve an accuracy better than 2%.

A second experiment was conducted to demonstrate that the ground contact force can be kept constant independently of the leg angle. To this end, the desired support force $F_{s,des}$ was set to 23 kN, the joint angle $\varphi_1$ was manually moved from $-7^\circ$ to $40^\circ$, and the actual ground contact forces were measured using the industrial balance. As shown in Fig. 10, the measured force from the balance (blue line) deviates maximally 0.7 kN from the constant desired ground contact force (red line) while the cylinder force (green dashed) is appropriately changed as a function of the joint angle.

VI. FORCE DISTRIBUTION AND INCLINATION CONTROL

With four legs in simultaneous ground contact, a quadrupedal robot theoretically features six internal forces. This allows to change the ground contact force distribution without influencing the motion of the system [24]. Considering only the most important one, the reaction force in gravitational direction, there remains one internal degree of freedom to modulate the distribution without influencing the net vertical force as well as the moment around the roll and pitch rotational direction. Hence, the most simple, still versatile force control setup for the walking excavator involves only the automated adjustment of the two jack cylinders of the back legs (red label in Fig. 11), which directly produce the torque around the first flexion-extension joint (blue arrow). Active control of these two cylinders enables simultaneous control of the pitch angle ($\theta$, yellow) and ground contact force distribution.
A. Virtual Model Pitch Control

A virtual force $F_v$ which should be produced by the two hind legs is calculated as a function of the inclination $\theta$ and the gravity compensation force $F_{gc}$:

$$F_v = K_\theta (\theta_0 - \theta) + F_{gc}. \quad (7)$$

$F_{gc}$ is not only a function of the mass of the excavator. It can vary up to 50%, depending on the load in the bucket and the unknown configuration of the upper machine part. Fortunately, since the motion of the system can be approximated as quasi-static, $F_{gc}$ can be measured at runtime by adding up the forces at hind right (HR) and hind left (HL) legs. To filter out undesired dynamic effects and sensory noise, this force is additionally lowpass filtered (IIR, first order):

$$F_{gv}^i = \alpha (F_{HR}^i + F_{HL}^i) + (1 - \alpha) F_{gv}^{i-1}. \quad (8)$$

B. Force Distribution

In a second step, the virtual force $F_v$ is distributed over the hind legs according to the force distribution measured at the front right (FR) and front left (FL) legs:

$$F_{HR} = \frac{F_{FR}}{F_{FR} + F_{FL}} F_v = \eta_{FR} F_v \quad (9)$$

$$F_{HL} = \frac{F_{FL}}{F_{FR} + F_{FL}} F_v = \eta_{FL} F_v. \quad (10)$$

This creates a virtual contact point or center of pressure (CoP) positioned between the two hind legs such that the machine is virtually supported by a triangle. The location of the CoP is determined by the base line $b$ and the distribution factors $\eta$. At an equal distribution (which corresponds to a mechanical swing axle), the CoP is in the middle (Fig. 12, black); if the boom and hence the CoG is rotated to the left respectively right of the machine, the CoP is shifted to the left (red) respectively right (blue) of the machine. This mechanism effectively shifts the tilting axle of the support triangle such that stability is ensured at all time.

C. Operator Control

The operator input at the front legs can be used for feedforward compensation to improve the dynamic response:

$$F_{FF,HR} = F_{FF,FR} \quad (11)$$

$$F_{FF,HL} = F_{FF,FL}, \quad (12)$$

with $F_{FF}$ being a tuning factor to achieve a smooth behavior and $u_{FR}$ respectively $u_{FL}$ $\in [-1,1]$ the valve opening signal for the front jack cylinder given at the operator joystick.

VII. Experiments

The following set of experiments which are considered as the most relevant working tasks in daily operation were conducted with the identical control setup and parameters. To get a good performance evaluation of the active balancing mechanism, all tasks were additionally executed by the most experienced driver at Menzi Muck AG. They are documented with a movie\textsuperscript{1}.

\textsuperscript{1}http://youtu.be/fKRkJUX6sA2M
D. Moving on Uneven Ground

Finally, the excavator was tested when partially moving on an inclination (Fig. 15(b)). This is a typical working situation which involves manual adjustment of the front legs and automated adaptation of the hind legs.

As illustrated in Fig. 17, even a very experienced driver is not capable to achieve an acceptable distribution of the weight on all four wheels when driving manually (blue). The force distribution entirely shifts from the left to the right.

With activated contact force adaptation, the supporting forces remain evenly distributed. Moreover, the driver only needs to control the front legs to adjust the roll angle or body height. Tracking errors in the force and hence change in the ratio of the forces over the hind legs equally. As shown in Fig. 16(a), the support force distribution \( \eta_{HR} \) at the right hind leg drops below zero in the uncontrolled (yellow) and manually controlled (blue) case, implying that the leg carries no mass of the chassis \( (F_{HR,s} < 0) \). With the activated controller (red), the cabin remains leveled (Fig. 16(b)), the joint angle \( \varphi_{HL1} \) is adapted (Fig. 16(c)), and the force ratio \( \eta = 0.5 \) stays constant (Fig. 16(a)).
In this paper we presented a clever force control method for the two jack cylinders of the hind legs of a walking excavator. The proposed method accurately levels out the chassis weight between the support wheels to ensure stability and to avoid unnecessary peak contact and cylinder forces. This assistance system can be activated or disabled upon the operators request and does not reduce versatility of the system in any case since the operator always keeps full control over the machine.

While a thorough user end-study could not be conducted in the context of this study, the proposed assistance system has been very well received by all users. It is very intuitive and needs no additional explanation to be used. The outstanding benefit was the fact that the active controller allows to move the excavator across obstacles while being constantly stabilized on four legs. Thereby, the operator does not have to worry about appropriate adjustment of the support legs but can fully concentrate on the excavating task.

An important outcome for coming research is the accurate force controllability that can be achieved with standard construction machine valve components and purely based on pressure sensing. We could show that frictional effects contribute only to about 1% of the maximal cylinder force. With our system, we can control the ground contact force to an accuracy of less than 150kg, which corresponds to 1.25% of the empty machine weight. With this tool at hand, our next steps will involve simultaneous control of all chassis cylinder and hence potentially full automation of the machine.

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Fig. 17: Force distribution ratio of the hind cylinders when driving up and down the ramp.

VIII. CONCLUSION