High-Resolution Indirect Feet–Ground Interaction Measurement for Hydraulic-Legged Robots

Samir Nabulsi, Javier F. Sarria, Hector Montes, and Manuel A. Armada

Abstract—Feet–ground interactions influence the legged robot’s stability. In this paper, a high-resolution indirect force measurement for hydraulic-legged robots is presented. The use of pressure transducers placed at one or both chambers of the robot’s double-effect hydraulic actuators is investigated, and conclusions are drawn regarding their capability for indirectly measuring the contact forces between the feet and the ground. Because of the nonlinear dynamic properties of hydraulic cylinders, friction modeling is essential to determine at all times the true forces of each foot against the soil. The test case is called ROBOCLIMBER, which is a bulky quadruped climbing and walking machine able to carry heavy-duty drilling equipment for landslide consolidation and monitoring works. Sensor calibration and signal filtering requirements are also taken into consideration. To end, the overall proposed approach to measure feet–ground interactions is experimentally evaluated.

Index Terms—Feet–ground interactions, friction modeling, hydraulic actuators, pressure sensors, quadruped robot, signal filtering.

NOMENCLATURE

Notation for hydraulics

- $x_p$: Differential cylinder piston position.
- $\phi_{\text{piston}}$: Differential cylinder piston diameter.
- $A_A$: Differential cylinder chamber A area, piston side.
- $A_B$: Differential cylinder chamber B area, rod side.
- $A_p$: Piston area (used sometimes instead of $A_A$).
- $V_{A,B}$: Differential cylinder chamber volumes.
- $\alpha = A_B / A_A$: Dimensionless factor relating both chambers.
- $F$: Force.
- $p_{A,B}$: Differential cylinder pressure (chamber A, B).
- $k$: Pressure sensor conversion factor.

Notation for the Kalman-based filter (KBF) equations

- $\hat{x}_k$: Updated process state vector estimate.
- $P_k$: Error covariance matrix.
- $K_k$: Kalman gain (blending factor).
- $H$: Matrix giving the ideal (noiseless) connection between the measurement and the state vector.
- $Q_k$: Covariance matrix.
- $R_k$: Variance matrix.
- $\epsilon_k$: Prior covariance error.
- $u_k$: Vector assumed to be a white sequence with known covariance structure.
- $\Phi$: State transition matrix.

I. INTRODUCTION

Research on walking and climbing robots has received great attention during the last decade [1]–[4], and a broad spectrum of applications have been reported in the literature, which range from shipbuilding [5], [6] and construction industry [7] to many others [8], [9]. Moreover, future applications of service robots entail in a relevant manner the development of climbing and walking machines [10], [11]. In particular, climbing robots could provide construction industries with useful tools to decrease human exposition to harmful working conditions and to increase productivity [12]. Rocky slope consolidation to avoid landslides is required before undertaking other infrastructure works (e.g., road, rail, and buildings). However, the current practice for slope consolidation involves dangerous labor-intensive operations based on deep drilling using heavy-duty machinery to get holes at geologically selected locations in the slope. Such holes (up to 20 m in depth) are filled in with concrete, which reinforces the slope and, therefore, consolidates it and avoids landslides. Steel networks are then put in place to finish the work [12]. ROBOCLIMBER (Fig. 1) is a quadruped walking and climbing robot whose development was funded by the European Commission under a Cooperative Research Program with the objective to develop a teleoperated service robotic system that could safely perform slope monitoring and consolidation tasks [13], [14].

The robot is based on a mechanical structure [15] that is supported by four legs, where each leg provides three degrees of freedom in a cylindrical kinematic configuration (Fig. 2). Each of the legs is able to support a total load of more than 15 000 N, and they are all able to carry the drilling unit and other auxiliary equipment onboard, which lead to an overall weight of 4 tons. ROBOCLIMBER (a good report was released by Discovery Channel [16]) can work by walking and even climbing uneven mountain slopes with inclination ranging from 30° to almost 90°, and in this case, it is being held from the top of the mountain by two steel ropes, each of which is anchored to a certain
Walking or climbing over flat surfaces could be achieved by using appropriated gaits, but even in this ideal case, and mostly due to robot mechanical imperfections, the robot’s movements result (generally after a short number of cycles) in loosing the robot’s attitude and instability [19].

To solve this problem, legged robots are equipped with some kind of on–off contact sensors at their feet, and using this simple information, it is possible for the robot to walk and climb over uneven surfaces by stopping the leg when the foot contacts ground or leaving it to go further the theoretical trajectory set point until contact is detected. However, this solution is not perfect, and there are many practical situations [e.g., due to a change in the working conditions (load and posture)] where this approach is not enough. A significant case is when perforation rods are being drilled into the mountain slope. Their weight accounts to one-third of the robot weight, so this very much affects the payload distribution. Moreover, reaction forces in the orthogonal direction to the slope are expected to change in a difficult-to-predict manner during drilling (involving hitting) and all through removing the drilling rods from the rocky slope. This will result in uncontrolled feet–ground contact loosing, which translates into undesirable robot vibrations. Moreover, the uneven surface requires using the third joints (vertical) of the legs to adjust and control the drilling unit orientation to be as close as possible to 90° against the slope. Moreover, a robot of ROBOCLIMBER proportions could be useful for many other applications (apart from drilling), for example, in the exploration or transport of equipment through hazardous areas. This yields to changing the total mass of the robot and to changes in their center of gravity, which lead to gait stability problems. Therefore, it is required to propose other methods to overcome the problem.

One possible solution is to consider feet–ground contact force measurement, where we feedback this measurement information into the robot control system [20] to implement control strategies to solve the aforementioned problems. For example, one of the most important applications could be controlling the overall force distribution, which will allow controlling the momentum about the robot axis; this being very important both for walking on uneven terrain and particularly for climbing on rough slopes [19]–[21]. Therefore, the first matter is to use vertical joints with force-sensing capability. Furthermore, because of the wide range of possible working situations for ROBOCLIMBER [21], force measurement in the other two joints has also been under consideration with the goal of controlling the overall force distribution and allowing the implementation of force control algorithms for controlling the robot–environment interaction [22], [23].

### III. INDIRECT FEET–GROUND INTERACTION MEASUREMENT USING PRESSURE SENSORS

The ROBOCLIMBER control system employs position feedback that is provided by 12 high-resolution encoders to measure prismatic joint excursions (joints 2 and 3 of each leg: 0.1-mm resolution) and rotation angle (joint 1 of each leg: 10,000 counts per revolution) to control with high accuracy the robot movements using 12 digital PID controllers tuned (independently)
for each joint [18]. The output of the position PID controllers (a pulse width modulation (PWM) signal) is converted to an analog signal and fed to another set of 12 power servoamplifiers that process these signals through another PID compensator that provides PWM signals to control the proportional valves (an internal current feedback loop is used to smooth the intensity to the solenoids). Proportional valves provide controlled oil flow into the differential hydraulic cylinders (oil ports A and B), which results in piston positioning. Fig. 3 shows a diagram of the ROBOCLIMBER’s vertical link of one leg, which is made of steel subassemblies with the hydraulic cylinder inside. It consists of two frames that slide against the other. The piston rod has attached at its free end one foot that contacts the ground.

As previously explained, we are first interested in the measurement forces along the robot $z$-axis. One possible solution has stemmed after analyzing the force analysis acting on the leg foot (Fig. 3) [22], [23]. It can be inferred from this analysis that the extension of the prismatic joint is made by the hydraulic pressure inside the cylinder’s chamber, and therefore, this hydraulic pressure is the pressure that supports the weight of the robot. Therefore, a method to obtain information about contact forces is to use pressure sensors placed at one or both ends of the chambers (oil ports A and B, Fig. 3) of the differential cylinders and to obtain an indirect estimation of the contact forces. The transducers usually employed to convert the hydraulic pressure into electrical signals are the so-called pressure transducers. The main advantage of these kinds of transducers is that they are low cost, easy to install, reliable, and provide good precision, but, of course, the different properties of the overall hydraulic system behavior should be taken into account [24]–[29]. Table I shows some technical data of the ROBOCLIMBER. The next sections discuss the use of sensors in one or two of the oil ports.

### A. Force Measurement Using Pressure Information From One Chamber

For our application, hydraulic GEMS 2200 pressure sensors with an operating pressure range between 0 and 100 bar, providing a signal from 0 to 5 V, and with 0.25% precision and thermal error of 1.25% (full scale) were selected. The first approximation consisted of the measurement of the force $F_A$ supported by the upper chamber of the hydraulic cylinder for each leg (Fig. 3) using only one transducer at oil port A and measuring the force according to

$$F_{pA} = p_A \cdot A_A$$

(1)

where $A_A$ is the piston area (Table I), and $p_A$ is the pressure measured with the sensor just placed at oil port A. With the selected sensor, it is then possible to have a theoretical sensitivity of 96 N.

The pressure sensor output signal is processed by a modular instrumentation amplifier that combines high accuracy, low noise, high-precision gain, high linearity, and temperature compensation. Because the leg manufacturing process is not ideal, a tuning process has to be done on the amplifiers for all legs to perceive with high-resolution interaction forces independent of mechanical differences. The purpose of the tuning process is to find the relationship between the output signal of the amplifier ($V_{out}$) and the pressure ($p$), which aims to adjust dc bias, amplifier gain, and bandwidth. The tuning method consisted of using one leg at a time, which leaves the others raised (no ground contact). Then, the subject leg is vertically moved with the foot contacting a calibrated reference load cell (maximum payload of 30 000 N, 10-N precision, and 1.7 N of standard deviation), and using (1), the force measurements provided by the load cell are converted to pressure. This tuning has the advantage (and the goal) of compensating, in some way, the inherent inaccuracies of using pressure measurement in only one chamber to simplify the sensor setup (and to decrease cost).

The values of each of the devices were gathered in real time. Given the pressure equation [where $k$ is the pressure conversion factor $\left(20 \times 10^5 \text{ N/(m}^2 \text{ x V)}\right)$], we have

$$p = k(aV_{out} + b).$$

(2)
A linear regression was done with the Matlab Curve Fitting Tool using the data obtained during the tuning process. The result is graphically shown in Fig. 4, and the $a$ and $b$ parameters for each leg are listed in Table II.

To evaluate and eventually better understand the possible limitations of using only one pressure sensor, several experiments were conducted. The robot was equipped with four sensors at oil port A of the vertical joints. The first experiment consisted of raising the robot on four legs under velocity control and in several steps from its rest position (robot body frame contacting ground, feet up), to several new positions, stopping some time at each one, and proceeding to the next. The results are shown in Fig. 5.

The first thing to notice is that the control system perfectly keeps each vertical joint position, but there is a clear force decay that is motivated by a pressure decay inside chamber A, and as a consequence, the apparent weight of the overall machine is decreasing very slowly with time in a significant amount and converging slowly to a stationary value that matches the actual machine weight. While this could be useful in other practical cases [26], [27]), and we foresee the need to take into account what happens inside chamber B. Additionally, other phenomena due to pressure distribution across the hydraulic circuit could be taken into account. To overcome those inconvenient situations, which are noticeable from the obtained results, the use of differential pressure measurement is proposed in the next section. In addition, friction modeling will be accomplished in the subsequent section.

B. Force Measurement Using Pressure Information From Two Chambers

One way to minimize the effects of pressure variations inside

\[
F_z = F_p(p_A, p_B) = F_{pA} - F_{pB} = (p_A - \alpha p_B)A_p. \quad (3)
\]

$A_p$ is the area of the piston, and $\alpha$ is the differential factor between both chambers [27] (please refer to Table I for actual parameter values). The sensor at oil port B is connected to the port through a rigid pipe from the oil port A to the port through a rigid pipe at about 0.7 m from the port. Connections from both sensors to the hydraulic power unit are by means of a combination of flexible hoses and rigid pipes. The length of such a hydraulic circuit is several meters.

To notice the effect in force measurement using the pressure difference from both sides of the piston, the cylinder was subject to a sinusoidal reference input in speed. In this case, the effects introduced by acceleration are liberalized, but this does not happen with friction effects, as can be noticed in the recorded graphic (Fig. 7). This experiment was realized in the same conditions like the previous experiment, and it is possible to notice that both leg speed and force at chamber A are the same (Fig. 6). In addition, it is interesting to point out that the resulting force values are actually more clearly connected with the inner load in movement. The negative sign for resultant forces in Fig. 7 needs to be interpreted just as a convention to indicate the direction of movement (force projection against robot reference frame).
As a conclusion, the force $F_p$ computed using the pressure difference signal is well suited to measure the “true” contact force and should be preferred to the use of only one transducer at chamber A or B. The use of two transducers also has additional advantages.

1) Temperature effects are minimized when friction measurements are used. Temperature variations dramatically change the oil viscosity, but differential measurement minimizes that effect.

2) Low-velocity measurements are now more reliable and accurate (under 5 mm/s), whereas with only one chamber measurement, speed measurement is always problematic. This is very important, for example, when implementing force control strategies.

3) In addition, as a third advantage, this approach does not require perfect parameterization of friction, which simplifies the computation.

IV. FRICTION MODELING

As it is well known, one of the main nonlinearities of the cylinder model is nonlinear friction [27]–[29]. To understand the influence of friction in the overall response of the cylinders, a standard method to counteract the influence of friction against the measurement of the differential pressure on the hydraulic fluid is to measure the force actuating in the joint without the influence of any external load during the displacement with a certain velocity $\dot{x}_p$ according to the Stribeck model [26]–[28]

$$F_f(\dot{x}_p) = F_v(\dot{x}_p) + F_c(\dot{x}_p) + F_s(\dot{x}_p)$$

$$= \sigma \dot{x}_p + \text{sign}(\dot{x}_p) \left[ F_{c0} + F_{s0} \exp \left( -\frac{|\dot{x}_p|}{c_s} \right) \right].$$

In (3), the friction force is made up of three different parts with the following meaning:

- $F_v$: viscous friction;
- $\sigma$: parameter for viscous friction;
- $F_c$: Coulomb friction;
Fig. 8. Results of friction modeling experiments for vertical links.

\[ F_{c0} \quad \text{parameter for the Coulomb friction;} \]
\[ F_s \quad \text{static friction;} \]
\[ F_{s0} \quad \text{parameter for the static friction;} \]
\[ c_s \quad \text{parameter for the static friction, known as the Stribeck velocity.} \]

To take into account the differential cylinder asymmetry, it is convenient to use a modification of (4) as follows:

\[
F_f(x_p) = \begin{cases} 
σ^+ x_p + \text{sign}(x_p) \left[ F_{c0}^+ + F_{s0}^+ \exp\left(\frac{|x_p|}{c_s}\right)\right] & \forall x_p \geq 0 \\
σ^- x_p + \text{sign}(x_p) \left[ F_{c0}^- + F_{s0}^- \exp\left(\frac{|x_p|}{c_s}\right)\right] & \forall x_p < 0,
\end{cases}
\]

(5)

It is possible to experimentally identify friction parameters by finding the relationship between the velocity of the joint and the measured force. Usually, this identification must be done without any additional payload and in horizontal position (without the influence of gravity), and in this case, it is possible to easily find the parameters associated with friction [27]. However, in our case, the friction modeling process has been done by leaving the vertical joint in its regular position without being uninstalled from the robot structure, where it is possible to model the effects of the mechanical structure of the joints, like the weight of the inner joint bodies, the structural mechanical friction of the prismatic joint, and the gravity effects. Aiming to that purpose, for the model identification of one of the vertical joints, the cylinder has been actuated in different positive and negative velocities, without touching the ground with the foot, while the forces were measured.

Fig. 8 shows the results of the experimental modeling of the actuator friction, and it is possible to notice that for each of the velocities in which the force (differential pressure) has been measured, the force is not around a certain point but among a wide set of measurements. This is because the friction force not only changes according to the velocity but according to the extension of the hydraulic cylinder (it depends on its position; this theoretical assumption [27], [28] is well corroborated here by experimentation), where there is a difference among the fluids in each chamber at each instant.

Table III shows the obtained Stribeck parameters for this experiment. These parameters were found out by an approximation process (parameter tuning was done using simple identification algorithm [27], [28]), which defined the Stribeck-based behavior of the friction for a certain vertical prismatic joint.

In conclusion, it has been shown that a good modeling of friction has been accomplished through extensive experimentation. This work has been done for all robot joints.

In addition to the effects described before, there are different phenomena (e.g., fluid compression, stick-slip effect, etc.), other than the implicit signal noise, that influence the hydraulic system dynamics. Using the experimental setup with ROBOCLIMBER, some of these effects have been studied (Fig. 9). Although they do not necessarily have to be taken into account for a hypothetical force control system, they are of interest to better understand the actuator behavior.

V. SIGNAL FILTERING

For reactive control purposes, it is needed to handle signals that could provide accurate and reliable force measurement with high resolution. This obviously implies signal filtering. Being the previous sections devoted to understand and to model the hydraulics, and to investigate the best way to obtain precise measurements of feet–ground interactions, some considerations on filtering for this application are herein presented. After having good experimental information about the involved signals in our problem, some first- and second-order digital filters have been tested; even different types of Kalman filters have been tested too. However, after preliminary trials, it has been decided to use a modified KBF [30], [31] to improve the quality of the force measurements based on the hydraulic pressure. This modified KBF (Fig. 10) is a digital recursive solution for real-time applications [31]. The process [Fig. 10, (1)] starts by giving a prior estimation of the process state vector \( x_{k-1} \), the error covariance \( P_{k-1} \), and the maximum threshold \( \epsilon_{\text{max}} \) determined for our system. It is assumed that at this point, it is in time \( t_k \), and that this prior estimate is based on our knowledge of the process before \( t_k \).

The next problem is to find the particular blending factor \( K_k \) (Fig. 10, (2)) that yields an update estimate that is optimal in some sense. This estimation can be controlled by the variance \( R \), which in our case can be assumed constant and was experimentally obtained.

Table III

<table>
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<th>Parameters</th>
<th>( x_{k&gt;0} )</th>
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<tr>
<td>( \sigma )</td>
<td>6.25</td>
<td>11.67</td>
</tr>
<tr>
<td>( F_{c0} )</td>
<td>-280</td>
<td>-700</td>
</tr>
<tr>
<td>( F_{s0} )</td>
<td>100</td>
<td>-250</td>
</tr>
<tr>
<td>( c_s )</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>
Fig. 9. Example of force signal obtained using differential pressure measurements and identification of fluid compression and stick-slip phenomena (horizontal axis means time in seconds, vertical scale means force in newtons).

With the assumption of a prior estimate $\hat{x}_{k-1}$, it is necessary to use the actual measurement $z_k$ to improve the prior estimate $\hat{x}_{k-1}$ (4). However, the different types of effects actuating in the hydraulic circuit can degenerate this estimation because most of these effects cause high peaks in $z_k$. Therefore, to improve the measurement by taking into account the external effects, additional control estimation has been added to improve the robustness of the filter where $\hat{x}_k$ would not be updated if the covariance error $e_k$ overpasses $e_{\text{max}}$ [Fig. 10, (3)], where

$$e_k = z_k - \hat{x}_{k-1}.$$  \hfill (6)

The next step is to evaluate the error covariance vector $P_k$ associated with the updated estimate [Fig. 10, (5)]. Finally, the process must update the future state vector $\hat{x}_{k+1}$ and covariance vector $P_{k+1}$ [Fig. 10, (6)], which is evaluated with a constant covariance matrix $Q_k$ (which, in this case, is also assumed constant and experimentally determined).

The significant effectiveness of the filter can be changed by modifying the $R$ and $Q_k$ values. If $R$ is increased, then the measurements prior to $t_k$ will have more influence over $x_k$, and if $Q_k$ increases, then the influence of the actual measurement will increase too. For the experimental results presented in the next section, $R$ and $Q_k$ values were determined through many trial-and-error testing. This was enough for our present purposes.

**VI. EXPERIMENTAL RESULTS**

This section is devoted to a final experimental verification of the proposed methodology. To do that, the experiment will consist of trying to obtain a signal that only represents the actual force acting on the system (one actuator), which filters out undesirable dynamic effects. Moreover, it will be shown that an additional KBF provides definitive results.

**A. Friction Modeling**

It is possible to measure the force acting on the cylinder without the dynamic effects by only measuring the external payload using the following equation, where nonlinear friction is introduced [27], [28]:

$$F_{\text{ext}}(p_{A}, p_{B}, \dot{x}_p) = F_p(p_{A}, p_{B}) - F_f.$$  \hfill (7)

To verify the result of using the Stribeck-model-based function, the same example of the sinusoidal movement of the joint (please refer to Fig. 7) has been used, subtracting from the differential force signal the friction-based Stribeck model.

As it is possible to notice from the force behavior (see Fig. 11), the results form the external forces measured from the differential forces, and the friction parameterization of the vertical joint are very acceptable, where the forces of the joint are around zero when there is no external payload acting. However, there are still some high and low peaks. These peaks are the result of the behavior of the hydraulic system when the cylinder is actuating at low velocities, where it is very difficult to model the system [26].

**B. Signal Filtering**

As explained before, a suitable way to take advantage of the KBF to filter complex signals is to add a threshold in the covariance error $e_k$. The problem is that in the hydraulic system, there are many external effects that are exhibited in the pressure, and in consequence, in force evaluation. Most of these effects are shown in the form of high peaks.
Fig. 11. Illustration of the use of friction modeling.

Fig. 12. Illustration of filtering approaches applied to force measurements.

TABLE IV
PARAMETERS FOR THE FILTERING PROCESS

<table>
<thead>
<tr>
<th>Parameters</th>
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</tr>
<tr>
<td>Q_k</td>
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<td>1</td>
</tr>
<tr>
<td>e_max</td>
<td>-</td>
<td>50</td>
</tr>
</tbody>
</table>

As an example, Fig. 12 presents a graphic that shows the difference between a filtered signal with a discrete KBF and the signal filtered with the proposed modified KBF and its R_k parameters Q_k, and the maximum threshold in the second case e_max (Table IV). As it is possible to notice, with the modified KBF, the filtered signal follows the same tendency of the original signal, but avoiding the dynamic effects of the low velocities in the hydraulic actuator.

VII. Conclusion

Force measurement is a very important issue in the development process of a semiautonomous walking robot for the improvement of its robustness. ROBOCLIMBER is a heavyweight quadruped robot designed for performing complex operations over natural terrain, where it is necessary to use robust and reliable sensor systems.

Instead of creating or installing any external force sensor, a proper solution is to use the hydraulic system properties to compute the force generated by the joints of the system. This force is evaluated by measuring the pressure in the hydraulic flow of the joints’ oil ports of actuators. The hydraulic pressure transducers are well known in the market, relatively cheap, and easy to adapt in the hydraulic circuit.

However, the problem is that when the pressure in the hydraulic system is measured, not only the dynamic effects of the hydraulic components affect the system, but also any unknown behavior of the complete system is intrinsically incorporated and so measured in the pressure signal.

That is why it is so important to understand the hydraulic system behavior and the most important effects that can originate alterations in the system. In this paper, some of the most important effects associated with the practical use of hydraulic actuators have been studied, which are mostly concentrated in the vertical links of the ROBOCLIMBER whose free ends are the feet that interact with the ground. It has been shown how proper friction modeling is required, because it greatly influences the system response. The method used to model the friction in the vertical joint is also applicable to the other joints of the system, although that has been omitted here for brevity.

Another important issue was to investigate the use of one or two pressure sensors. For accurate and dynamically representative force measurements, it can be concluded that the use of two sensors is the only choice for our application.

To improve the precision and reliability of the signals provided by the friction model, and after many digital filter analysis, for this application, the use of the modified KBF has been proposed.

With those results, it can also be concluded that, for hydraulic-legged robots, the indirect force computed with the proposed methodology presents significant advantages in terms of accuracy, reliability, simplicity, and low cost when compared with previous approaches of direct force measurement using load cells [21], [22].

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References

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