

# A Survey on Control of Hydraulic Robotic Manipulators with Projection to Future Trends

Jouni Mattila, Janne Koivumäki, Darwin G. Caldwell and Claudio Semini

**Abstract**—This paper presents the recent advancements in the control of multiple-degree-of-freedom ( $n$ -DOF) hydraulic robotic manipulators. A literature review is performed on their control, covering both free-space and constrained motions of serial and parallel manipulators. Stability-guaranteed control system design is the primary requirement for all control systems. Thus, this paper pays special attention to such systems. An objective evaluation of the effectiveness of different methods and the state of the art in a given field is one of the cornerstones of scientific research and progress. For this purpose, the maximum position tracking error  $|e|_{\max}$  and a performance indicator  $\rho$  (the ratio of  $|e|_{\max}$  with respect to the maximum velocity) are used to evaluate and benchmark different free-space control methods in the literature. These indicators showed that stability-guaranteed nonlinear model-based control (NMBC) designs have resulted in the most advanced control performance. In addition to stable closed-loop control, lack of energy efficiency is another significant challenge in hydraulic robotic systems. This paper pays special attention to these challenges in hydraulic robotic systems and discusses their reciprocal contradiction. Potential solutions to improve the system energy efficiency without control performance deterioration are discussed. Finally, for hydraulic robotic systems, open problems are defined and future trends are projected.

**Index Terms**—robotics, hydraulic manipulators, force control, motion control, performance evaluation.

## I. INTRODUCTION

ROBOTICS technology is expected to dominate the coming decade and its market is projected to grow substantially [1]. Advanced robotic systems are currently receiving a vast amount of attention in industry and academia. For example, driverless robotic cars are already being tested on the road [2], and many leading automotive companies have made significant investments in this technology [3]. In hydraulics, the robotics company Boston Dynamics robots (e.g., Atlas [4], BigDog [5] and Petman [6]) have already advanced the field of robotics. Academic research in advanced hydraulic robotic systems is also ongoing, e.g., IIT's *HyQ* [7] and *HyQ2Max* [8], Boston Dynamics' Atlas studied by MIT [9] (and other universities), Shandong University's *S calf* [10], Ritsumeikan University's *Tae-Mu* [11] and walking excavator studied by ETH Zurich [12]. In addition to these advanced high-tech hydraulic robots, hydraulic actuation has been used for decades in a variety of mobile (off-highway) working machines (e.g., construction, forestry, mining and agricultural machines) due to their

higher robustness and significantly larger power-to-weight ratio compared to electric actuators. It is highly expected that the advent of robotics will revolutionize this heavy-duty machine industry just as is currently happening in the car industry. In fact, the first commercial products, such as the Sandvik AutoMine® [13] for semi-autonomous underground mining machines and the John Deere Intelligent Boom Control (IBC) for forest machines [14], are already available on the market.

For the advanced robotic systems and working machines introduced above, hydraulic robotic manipulators and manipulator-like articulated structures (such as actuated legs) are crucially important subsystems because they can provide many versatile abilities, such as manipulation of the environment or legged locomotion. Furthermore, hydraulic actuators provide an attractive alternative to electric actuators to actuate these subsystems. This is because they are robust and can produce significant forces/torques for their size without concern of overloading. Comprehensive studies on actuator technologies for robotics can be found in [15]–[17]. Due to the great power-to-weight ratio of hydraulic manipulators, they are typically build for operations in which heavy objects (e.g., logs) are handled or tasks where large forces are exerted on the physical environment (e.g., excavation). In addition, for hydraulic robotic systems, such as those introduced in [4]–[7], [9]–[14], it is evident that free-space motion control alone is inadequate because the robotic system must be capable of controlling its interaction forces with the surrounding environment.

Section II presents an extensive survey on the control of multiple-degrees-of-freedom ( $n$ -DOF) hydraulic robotic manipulators (covering both free-space motion and constrained motion) and defines their current level of the state of the art. As addressed in [18], it can be very difficult to find good examples of replicable and measurable scientific research in robotics and automation. Miscellaneous reporting of results, without any unifying comparisons to the existing literature, makes an objective evaluation and benchmarking of the state of the art in a given field very challenging. In addition, objective performance evaluations would also speed up technology transfer between academia and industry, as well as promote the most advanced practices in a given field. In this paper, the normalizing performance indicator  $\rho$  (the ratio of the maximum position tracking error with respect to the maximum velocity) proposed by Zhu (see [19]–[21]) is used to benchmark different control methods in the literature for the control of hydraulic manipulators.

Despite the advantages of hydraulic actuation, two fundamental challenges in hydraulic robotic systems can be identified. First, *the dynamic behaviour of articulated hydraulic systems is highly nonlinear, making their closed-loop control*

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*design and stability analysis an extremely challenging task.* These systems may be subjected to non-smooth and discontinuous nonlinearities due to actuator friction, hysteresis, control input saturation, directional change of valve opening, or valve under/overlap; moreover, there are many model and parameter uncertainties [22]–[24]. The control design of hydraulic robotic systems is further complicated by the nonlinear nature of the associated multibody dynamics. Second, *traditional hydraulic closed-loop systems are not energy efficient.*

Section III pays special attention for the above two challenges and their reciprocal contradiction in hydraulic robotic systems. Achieving energy efficiency in these systems is challenging because control performance cannot be sacrificed in the process. Nevertheless, low energy consumption is essential to maximize the system operation time because energy source(s) must be carried on board in limited space. According to the literature review, all studies on high-performance closed-loop control of  $n$ -DOF hydraulic robotic manipulators have utilized servovalves. However, the very nature of servovalve control is dissipative, because it is accomplished by dissipating power via valve meter-in and meter-out throttling losses to heat energy [25]. Therefore, Section III discusses methods of how systems energy consumption can be reduced without (significant) control performance deterioration.

Section IV defines open problems in the control of hydraulic robotic systems and projects some future trends. Finally, Section V presents our conclusions.

## II. STATE OF THE ART IN HYDRAULIC ROBOTIC MANIPULATORS

As recently addressed in an article by Bonsignorio and del Pobil [18], in robotics, artificial intelligence, and automation, it is nowadays very difficult to find papers which are reproducible and where the results are evaluated with respect to the state of the art in a given field. In their opinion, this situation is detrimental to science and undermines one of the basic foundations of scientific research and progress. The following points are emphasized from [18]:

- “...the possibility of **reproducing results** is left to the good will of some authors.”
- “...closer to pure engineering applications, experimental proofs of the effectiveness of the proposed solutions are needed. We should at least be able to... **compare the results in terms of the chosen performance criteria.**”
- “...the difficulty of reproducing results—let alone comparing different methods and solutions—**slows down the industrial take-up** of new solutions.”

Unfortunately, these remarks on lack of reproducibility and evaluation of results with respect to the state of the art are also very apt for papers on the control of  $n$ -DOF hydraulic robotic manipulators.

In addition to this, *stability is the primary requirement for all control systems*, as asserted in [26]. Therefore, the main focus in this paper is to survey the state of the art in the field of the control of  $n$ -DOF hydraulic robotic manipulators, which 1) provides a stability-guaranteed control design and 2) supports the scientific cornerstones in [18]. In this paper, single-DOF

actuator control designs are not reviewed because, in general, they cannot provide a theory for  $n$ -DOF systems.

Next, Section II-A shows the state of the art in free-space motion control of hydraulic manipulators, covering both serial and parallel manipulators (see Figs. 1 and 2). Then, Section II-B shows constrained motion control methods proposed for hydraulic manipulators.

### A. Hydraulic Manipulators in Free Space Motion

This section presents methods in free-space motion control of hydraulic serial and parallel manipulators, followed by performance evaluations of these methods.

1) *Hydraulic Serial Manipulators:* As mentioned, the dynamic behaviour of hydraulic robotic manipulators is characterized by various nonlinearities. Thus, it can be inferred that nonlinear control methods are a necessity to achieve high-performance control for these systems. Indeed, Bech et al. [27] studied different linear and nonlinear controllers with hydraulic robotic manipulators and it was demonstrated that all nonlinear controllers delivered better performance than the best linear controller. In Bonchis et al. [28], ten different control strategies were evaluated with similar observations to [27].

A variety of *experimentally verified* free-space motion control strategies for hydraulic manipulators have been proposed, e.g., [19], [27]–[48]. However, from these studies only few papers have provided a sound control theory with a stability-guaranteed control design. As described next, these approaches are based on *Lyapunov methods* (backstepping) [27], [37], [38]<sup>1</sup> and on the  *$L_2$  and  $L_\infty$  stability method* [19], [43], [45].

Bech et al. [27] presented different nonlinear model-based control (NMBC) designs (based on a reduced-order system description) and the stability of the controllers were proven with the Lyapunov method. The designed controllers were 1) sliding mode controller, 2) adaptive inverse dynamics controller (AIDC), 3) AIDC plus PI-control, and 4) model-reference adaptive controller with velocity measurement (MRACV). In the experiment, MRACV displayed the lowest tracking error (but AIDC was almost as accurate). All nonlinear controllers outperformed five baseline linear controllers.

Based on backstepping [26], Bu and Yao proposed in [37] an observer-based adaptive robust controller (ARC) for hydraulic robotic manipulators. In [38], the ARC design was updated to a desired compensation adaptive robust control (DCARC). Both methods are NMBC methods and their stability analysis is based on the use of Lyapunov functions. In the experiments of [37] and [38], a three-link robot arm was used; however, in [38] two of the arm joints were fixed. Results in [38] demonstrated that DCARC yields less tracking error than ARC.

Zhu and Piedboeuf proposed in [19] an adaptive output force tracking control for a hydraulic robotic manipulator based on the virtual decomposition control (VDC) approach [51], [52]. Their adaptive NMBC design incorporated an adaptive friction compensation control. The rigorous stability proof was provided based on  $L_2$  and  $L_\infty$  stability. With a six-joint hydraulic

<sup>1</sup>Also, Becker et al. [49] and Zeng and Sepelri [50] have provided a Lyapunov-based stability proof for the control of hydraulic manipulators. However, in [49], only simulations were provided. In [50], the experiments were provided with only a single-axis hydraulic actuator.

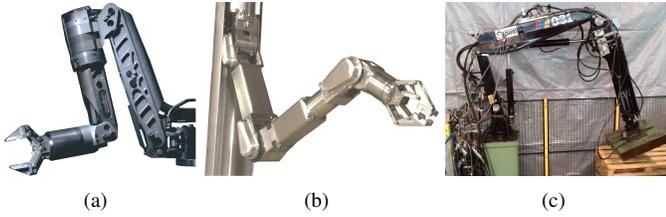


Fig. 1. Hydraulically actuated robotic serial manipulators: (a) Schilling ORION for underwater manipulation, (b) Cybernetix's MAESTRO for nuclear decommissioning and (c) HIAB031 for academic research purposes.

robot, the proposed control method demonstrated highly accurate joint pressure-based force and position tracking.

Koivumäki and Mattila [43] proposed a VDC-based controller for a two-DOF heavy-duty hydraulic manipulator. In [45], they demonstrated in three-DOF that by using VDC, more “subsystems” can be added to the original system without control performance deterioration and significant controller redesign. Both these stability-guaranteed NMBC studies demonstrated a position tracking performance improvement (using a performance indicator  $\rho$ ) in relation to [19] and [38]; see Section II-A3.

2) *Hydraulic Parallel Manipulators (HPMs)*: The Stewart-Gough platform (SGP) in Fig.2a is the most widely used parallel manipulator [53]. Fig.2b and Fig.2c show other examples of HPMs. HPMs inherit challenging features from both parallel manipulators and hydraulic actuators. On one hand, the main advantage of the closed-chain kinematics of the robot is that it distributes force among the limbs and can provide higher stiffness and acceleration. On the other hand, it makes all of the actuator motions constrained by the motion of the end-effector and have a limited workspace [54]. It is also well known that forward kinematics of parallel manipulators are challenging compared with the inverse kinematics of serial manipulators [55]. These issues are addressed in various controller topologies for different types of parallel robots where the dynamics of the actuator implies specific restrictions to the robot controller [56], [57]. Actuator redundancy, which is suitable for dexterity improvement, affects force distribution and kinematic structure; see the shoulder mechanism in Fig.2(b), which has three DOF and four actuators [55].

This section focuses on recent research in *experimentally verified and stability-guaranteed* NMBC design for the hydraulic SGP. A number of experimentally verified control strategies for HPMs, albeit without rigorous stability proof, also exist in the literature, e.g., [58]–[61]. For a review of parallel manipulators from their early days to the year 2000, the interested reader is referred to the work of Dasgupta and Mruthyunjaya [53].

Kim et al. [62] proposed one of the first studies on stability-guaranteed Lyapunov-based methods for a hydraulic SGP. In their robust tracking control design, stability of rigid body dynamics was proven, however, stability analysis of the actuator dynamics was neglected.

Sirouspour and Salcudean [64] tackled the above problem and proposed for the first time stability-guaranteed NMBC considering both rigid body dynamics and actuator dynamics. Adaptation laws were incorporated into the controller to compensate for parametric uncertainties in rigid body parameters

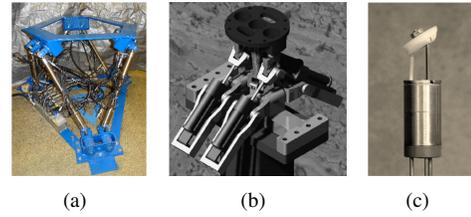


Fig. 2. Hydraulically actuated parallel manipulators: (a) IHA's six-DOF SGP, (b) Concept of a redundant shoulder [55] and (c) A miniature three-DOF SGP as a part of an endoscope [63].

and hydraulic parameters. Acceleration feedback was avoided by using two adaptive and robust sliding-type observers. Tracking errors were rigorously proven to converge to zero asymptotically using Lyapunov analysis. Very advanced control performance was demonstrated in experiments.

In [65], Pi and Wang proposed an observer-based cascade control. A cascade control algorithm was used to separate the hydraulics dynamics (inner-loop control) from the mechanical part (outer-loop control). Feedback linearization was used for the control of hydraulics nonlinearities in the inner loop. A nonlinear disturbance observer was proposed to estimate uncertain external disturbances. The stability of the inner loop control with nonlinear disturbance observer was provided based on the Lyapunov functions method. It was assumed that “some existing nonlinear control methods can be directly employed in the outer loop”.

In [66], Pi and Wang proposed a trajectory tracking controller with uncertain load disturbances. They designed a discontinuous projection-based parameter adaptation for parameters in hydraulic dynamics. Platform rigid body dynamics were neglected in the Lyapunov-based stability analysis.

Chen and Fu [67] proposed an observer-based backstepping control. Similar to [64], this method considered both the platform dynamics and the dynamics of the hydraulic actuators. An observer-based forward kinematics solver was applied to prevent transformation between different states in the platform dynamics (task-space) and in the actuator (joint-space) dynamics. As a distinction from [62], [64]–[66], a friction compensation was added in the controller. The rigorous stability proof for the system was given with convergence of control errors.

As the above review shows, papers [64] and [67] provide theoretically the most rigorous solutions for the control of parallel hydraulic manipulators. Next, the state of the art in hydraulic manipulators free-space motion control is evaluated for parallel hydraulic manipulators, as well as for serial hydraulic manipulators.

3) *Evaluation of the State of the Art*: Evaluation of results and the state of the art in the field of robotics and automation can be difficult [18]. The majority of the studies in Sections II-A1 and II-A2 have reported the maximum position tracking error(s)  $|e|_{\max}$  (in actuator space or Cartesian space). However, using the maximum position error alone to compare different control methods does not give a realistic picture of the control performance, because different sizes of manipulators were used with different rates of applied dynamics. In the survey of Patel and Sobl [68], a variety of performance measures for manipulators were introduced. However, they mainly focus on the evaluation of manipulator structure and

design (indices like workspace index, dexterity index, joint range availability and manipulability index).

A feasible way to evaluate the performances of the different control methods for  $n$ -DOF hydraulic robotic manipulators, is the performance indicator  $\rho$  that has been used in the studies done by Zhu (e.g., in [19]–[21]). This normalizing performance indicator is defined as

$$\rho = \frac{\max(|\mathbf{x}_{des} - \mathbf{x}|)}{\max(|\dot{\mathbf{x}}|)} = \frac{|e|_{\max}}{|\dot{\mathbf{x}}|_{\max}} \quad (1)$$

where  $\mathbf{x}_{des}$  is a desired position vector and  $\mathbf{x}$  is a measured position vector. The smaller the  $\rho$ , the better the performance. The index  $\rho$  quantify the tracking control performance of a robot. The rationale for selecting this index is that usually large velocities in the task space are associated with large accelerations, which in turn result in large position tracking errors considering the uncertainties in robot dynamics [21].

Tables I and II show the performance indicators in *actuator space*<sup>2</sup> and *Cartesian space*, respectively, for all serial manipulator studies amongst [19], [27]–[48], [50] where sufficient data to compute  $\rho$  was available. Table III shows the performance indicators in *Cartesian space* for all parallel manipulator studies amongst [58]–[62], [64]–[67], [69] where sufficient data to compute  $\rho$  in Cartesian space was available.

The first column in Tables I–III shows the corresponding study. The second column shows the value for performance indicator  $\rho$ . The third column shows the absolute maximum position tracking error. The fourth column shows the number of driven actuators. The fourth column shows if the control design is stability-guaranteed NMBC. The maximum velocity in the driven test trajectory can be calculated with (1) using the data in the second and third columns in Tables I–III.

As Tables I–III demonstrate, using the maximum position error  $|e|_{\max}$  alone as an indicator would not give a realistic picture of the actual control performance. This is demonstrated, for example with studies [35] and [45] in Table II, where roughly similar maximum position tracking errors exist. However, the maximum velocity in [35] is approx. 0.022 m/s and in [45] it is 1.05 m/s. Studies [59], [65], [66] in Table III demonstrate the same issue, as with nearly same  $|e|_{\max}$ , very different performance indicator  $\rho$  values are obtained.

As Tables I–III clearly show, stability-guaranteed NMBC methods outperform other methods in the control of hydraulic manipulators when free-space motion control accuracy is considered. Although these methods may need substantially more effort in their control design, they seem to be justified if high-performance dynamical behaviour is required. Based on the data in Tables I–III, it can be concluded that [19] and [45] provide the state-of-the-art control methods for the hydraulic serial manipulators. Similarly, [64] provides the state-of-the-art control method for hydraulic parallel manipulators. It is unfortunate that another rigorous parallel manipulator study [67] did not provided enough data to compute  $\rho$  for Table III.

<sup>2</sup>If the results for more than one actuator were given,  $\rho$  and  $|e|_{\max}$  are given for the best actuator. Note that the performance indicators in Table I might not give a realistic picture of the control performance of the entire manipulator, if large deviations occur between the actuators' control accuracy.

TABLE I  
 $\rho$  INDICATORS IN ACTUATOR SPACE FOR SERIAL MANIPULATORS

Study	$\rho$ [s]	$ e _{\max}$ [mm]	DOF	Stab. NMBC
Koivumäki 2015 [45]	0.0030 <sup>†</sup>	0.61	3	✓
Koivumäki 2013 [43]	0.0039 <sup>†</sup>	0.60	2	✓
Bech 2013 [27]	0.0044 <sup>*</sup>	2.05	2	✓
Zhu 2005 [19]	0.0050	‡	6	✓
Bu 2001 [38]	0.0050	0.50	1 <sup>°</sup>	✓
Conrad 1996 (AMAC) [33]	0.0087 <sup>*</sup>	‡	2	-
Mattila 2000 [36]	0.0130	2.00	2	-
Conrad 1996 (LPAC) [33]	0.0160 <sup>*</sup>	‡	2	-

<sup>†</sup>With the fastest trajectory data; see Fig. 13 in [45] and Fig. 1 in [43].

<sup>\*</sup>The maximum velocity is estimated from the sinusoidal desired position profile. See Fig. 4 and Fig. 14 (MRACV) in [27].

<sup>‡</sup> $|e|_{\max}$  is given in joint angle error (not in piston position error); 0.0005rad in [19], 0.12deg in [33] (AMAC) and 0.17deg in [33] (LPAC).

<sup>°</sup>The experiments were made with three-joint hydraulic arm, but two of the joints were fixed.

<sup>\*</sup>See Fig. 8(f) in [33] for AMAC and LPAC. It is mentioned in the text that the maximum velocity was limited to 2 rad/s.

TABLE II  
 $\rho$  INDICATORS IN CARTESIAN SPACE FOR SERIAL MANIPULATORS

Study	$\rho$ [s]	$ e _{\max}$ [mm]	DOF	Stab. NMBC
Koivumäki 2015 [45]	0.0050 <sup>†</sup>	5.20	3	✓
Zhu 2005 [19]	0.0150	1.50	6	✓
Egeland 1987 [29]	0.0380	30.0	8	-
Chang 2002 [41]	0.0450 <sup>*</sup>	27.0	3	-
Kalmari 2015 [48]	0.1200 <sup>°</sup>	120	4	-
Tsukamoto 2002 [40]	0.1260 <sup>‡</sup>	13.51	6	-
Nguyen 2010 [35]	0.3200 <sup>*</sup>	7.00	4	-

<sup>†</sup>With the fastest trajectory data; see Fig. 16 in [45].

<sup>\*</sup>The maximum velocity is estimated from the sinusoidal desired position profile. See Figs. 10 and 16(a) in [41], and Fig. 6 in [35].

<sup>°</sup>The value for the maximum tracking error was selected after the first round when the tracking error was settled; see Fig. 5.4 in [48].

<sup>‡</sup>A circular reference trajectory with a radius of 0.17 m was driven with angular velocity  $\omega = \pi/5$  rad/s. Maximum trajectory error was 13.51 mm.

TABLE III  
 $\rho$  INDICATORS FOR PARALLEL 6-DOF MANIPULATORS

Study	$\rho$ [s]	$ e _{\max}$ [mm]	DOF	Stab. NMBC
Sirouspour 2001 [64]	0.0100 <sup>*</sup>	2.60	6	✓
Yang 2012 [61]	0.0190 <sup>†</sup>	0.61	6	-
Pi 2011 [66]	0.0357 <sup>°</sup>	1.40	6	✓
Guo 2008 [59]	0.0600 <sup>*</sup>	1.50	6	-
Pi 2010 [65]	0.0910 <sup>+</sup>	1.60	6	✓

None of the above studies contains detailed velocity data. Thus, the maximum velocities were approximated from the given sinusoidal position trajectory data.

<sup>\*</sup>From Fig. 6 in [64], <sup>†</sup>From Figs. 7 and 8 (Surge data) in [61], <sup>°</sup>From Fig. 14 (y-axis) in [66], <sup>+</sup>From Fig. 10 in [59], <sup>\*</sup>From Figs. 5 and 6 in [65].

As Tables I–III show, there is a clear interconnection between the stability-guaranteed NBMC design and cutting-edge control performance. Thus, stability-guaranteed NMBC design can possibly be a performance indicator on its own, that can promote state-of-the-art control solutions for the industry. The performance indicator used in this survey serves as the initial step to quantitate tracking control performances across different experimental platforms in a unified manner. Improvements toward more precise quantification are expected in the future.

### B. Hydraulic Manipulators in Constrained Motion

Despite considerable research during recent decades, control of physical interaction is still a challenging research issue [70], and contact control applications in  $n$ -DOF hydraulic robots are less common in comparison to free-space robot applications.

One of the most critical factors inhibiting the wide-spread use of contact task applications has been the control system stability problems [70]. In robotic contact control, one of the most significant reasons for unstable behaviour is that contact dynamics between the robotic system and the environment can be drastic while the robot's nonlinear dynamics are not considered rigorously [71]–[75]. Thus, with highly nonlinear hydraulic manipulators, an accurate system control plays an even more vital role (compared to the free-space control), suggesting the use of NMBC design methods.

The basic approaches for robotic force control can be divided into methods originating from hybrid position/force control by Raibert [76] or impedance control by Hogan [77]; historical overviews of robot force control can be found in [75], [78], [79]. Typically hydraulic manipulators are built to operate heavy objects (e.g., logs) or to exert large forces on the physical environment (e.g., excavation). So it is rather surprising that only few studies exist regarding constrained motion (contact force) control of hydraulic robotic manipulators.

Dunnigan et al. proposed a hybrid position/force control [80], an adaptive hybrid position/force control [81] and a self-tuning position and force control [82] for an underwater hydraulic manipulator. No stability proofs for the proposed controller designs were given.

Heinrich et al. [83] implemented impedance control, with a nonlinear proportional-integral (NPI) joint control for a hydraulic manipulator. Rigorous stability proof of the proposed controller design was not given.

Tafazoli et al. [84] (see also their related studies in [85], [86]) proposed an impedance control for a teleoperated mini-excavator based on a simple proportional-derivative (PD) controller. Stability proof for a simple PD impedance controller was provided, but it was limited to a single-DOF hydraulic cylinder acting on the environment.

Itoh et al. [87] proposed a minimal controller synthesis (MCS) algorithm for adaptive impedance control of hydraulic manipulators. The stability of the proposed method was provided based on the hyperstability theorem. Experiments with a two-DOF hydraulic robot, with end-effector attached force sensor, illustrated the validity of the proposed method.

A major step forward from the existing solutions was taken by Zeng and Sepehri [88] who proposed a nonlinear tracking control with internal force control for multiple hydraulic manipulators handling a rigid object. Their control design was based on backstepping and the stability of the entire system was proven. However, the stability analysis was limited to situations where connection to the held object has already been established. The experiments were carried out with two single-axis electro-hydraulic actuators, which were connected to the common object with spring mechanisms [89], thus preventing unilateral constraints from being formed.

Boaventura et al. [90]–[92] proposed an active impedance control for lightweight hydraulic legs in their quadruped robot HyQ. In their control designs, feedback linearization was used to linearize the relation between the control input and the controlled variable. A rigorous stability proof for the proposed controllers was not given. As an interesting contribution in [90], the concept of Z-width, i.e., the achievable range

of impedance to keep the system passive, was extended to (hydraulic) legged robots for the first time.

Koivumäki and Mattila [93] proposed a stability-guaranteed force-sensorless contact force/motion control for heavy-duty hydraulic manipulators. The highly nonlinear behaviour of the hydraulic manipulator was addressed with the VDC approach, and the hybrid motion/force control was used to control end-effector motions and forces in their own subspaces. The experiments demonstrated compelling tracking performance as predicted by the theory. In the proposed control design, switching from free-space to constrained motion was not needed.

In [94], Koivumäki and Mattila proposed a stability-guaranteed NMBC method for hydraulic manipulators for the first time covering both free-space and constrained motions. The impedance control was designed using the framework of VDC and a special connection between the control parameters and the targeted impedance behaviour was discovered, making stability-guaranteed hydraulic robot impedance control possible. Experimental results demonstrated that with the proposed method, the hydraulic manipulator was capable of adjusting its dynamic behaviour accurately in relation to the imposed target impedance behaviour. It is worth noting that a certain degree of efforts are needed in the initial stage of control design process for a successful application of VDC, as in [93], [94].

Evaluation of the methods for constrained motion control of hydraulic manipulators is much more challenging compared to that of free-space control. Different contact control methods (e.g., hybrid position/force control and impedance control) can greatly differ from each other (see [79]). Thus, it can be hard to find a normalizing indicator similar to  $\rho$ ; see Falco et al. [95]. To our best knowledge, normalized performance indicators similar to  $\rho$  in (1) have not been reported to evaluate control performance of different contact force control methods.

### III. ENERGY EFFICIENCY AND HIGH-PERFORMANCE CONTROL IN HYDRAULIC ROBOTICS SYSTEMS

Today, strict administrative regulations surround energy issues for the industry. For instance, the new EU directive for energy efficiency [96], effective since 2012, demands that EU countries reduce energy consumption at a rate of 1.5% per year. Similar targets have been set, e.g., by the 12th Chinese Five-Year Plan [97], which mandated that energy use should be reduced by 16% before 2016.

All the systems with state-of-the-art control performance mentioned in the previous section are inherently energy inefficient. In many industrial systems, especially in stationary applications, energy efficiency can be a secondary design objective compared to other performance requirements. However, the situation becomes different in mobile (off-highway) machines where energy source(s) must be carried on board in limited space. What makes energy efficiency challenging, especially in advanced robotic systems, is that it cannot be achieved at the expense of lower control performance. This section will analyze the trade-off between energy efficiency and high closed-loop control performance in hydraulic robotic systems.

Hydraulic robotic manipulators (and systems) contain hydraulic-powered actuators and hydraulic power transmissions system, i.e., hydraulic pump(s). Typically, the majority

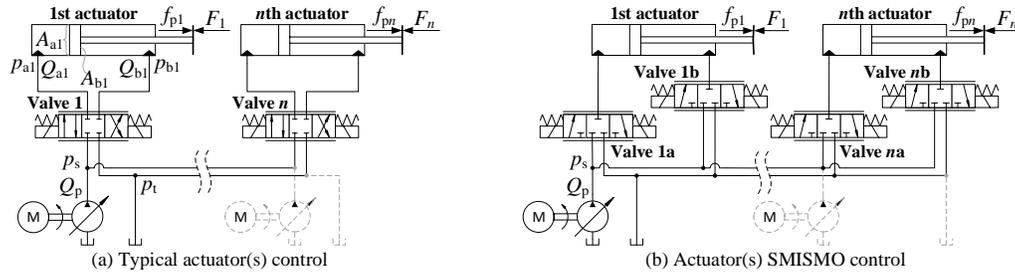


Fig. 3. Hydraulic diagrams for a typical cylinder(s) control (see subfigure a) and for a cylinder(s) SMISMO control (see subfigure b). Note that either one pump for all actuators or one pump per actuator can be used.

of hydraulic system power losses originate from the dissipative valve control of the system actuators. The most widely used high performance hydraulic systems use 4-way servovalve control powered by constant pressure sources; see Fig. 3a. The control principle in servovalves is accomplished by dissipating power via valve meter-in and meter-out throttling losses to heat energy and, thus, this method has inherent inefficiency in energy consumption. However, servovalve controlled systems are widely used because of their currently unmatched control performance required for closed-loop controlled  $n$ -DOF hydraulic systems, in terms of control accuracy and response time.

In displacement control [98], [99] and electro hydrostatic actuators (EHAs)<sup>3</sup> [100]–[102], a hydraulic actuator is controlled directly with the fluid flow rate of the pump, without using a load control valve between the pump and the actuator. Even though these methods can provide better energy efficiency, their dynamic response is typically much slower compared to that of servovalves [25]. Indeed, response times for cutting-edge variable displacement pumps (VDPs)<sup>4</sup> vary between 40–130 ms (see [103]), whereas the cutting-edge servovalves have a response time of 1.8 ms (see [104]). Furthermore, in studies [98]–[102] there is a lack of attention to high-bandwidth tracking performance which is essential for robotic purposes. However, it is valid to mention that recently Levant Power’s GenShock active suspension system (corresponding to EHA) has shown promising results in improving EHA’s dynamic performance [105]. However, no performance data has been published as of today.

It should be also emphasized that heavy-duty excavators and large loading cranes, e.g., in harbors are nearly stationary applications where actuator system weight and volumetric size are not the main design constraints but can rather be an advantage. In these high fluid flow with high inertia applications, controls can be found in which inefficient valve controls are often replaced with pump controlled motor that drives, e.g., swing axis gear ring. For excavator base swing, also hybrid actuator systems already exist on the market, e.g., by Caterpillar and Komatsu with claimed 25–33 % fuel consumption reduction [106]. However, to the authors’ best knowledge, no paper exist on  $n$ -DOF excavator or crane robotic closed-loop control that has swing function driven by pump/motor or hybrid

actuator. Very interestingly, [99] reports on “the world’s first prototype hydraulic hybrid excavator” implementation with all four machine actuators. The focus was only to demonstrate the concept energy-saving potential leading to the claimed impressive 50 % downsizing of the engine. The reported earth excavation cycles of dry test soil were driven manually by the operator and, therefore, a closed-loop control system was not implemented for the excavator manipulator that would have allowed a comparison. It is easy to foresee that in the near future, more research similar to [99] will be published.

Next, Sections III-A and III-B describe a possible solution for *hydraulic robotic systems that can decrease the system energy consumption without control performance deterioration*. This solution combines the benefits of servovalve control and displacement control. The solution is twofold. First, Section III-A introduces a method to reduce energy consumption of hydraulic actuators, however, still using servovalve control. Then, Section III-B discusses solutions to reduce the amount of supplied hydraulic energy in accordance to the reduced energy consumption of the actuators.

#### A. Energy Efficient Control of Hydraulic Actuators

Hydraulic actuators can be classified into cylinders (with linear output) and rotary actuators. In this section, a hydraulic cylinder is used as an illustrative example. From a theoretical point of view, understanding the interconnection between the actuator chamber pressures ( $p_a$  and  $p_b$ ) and the load force  $F$  and supply pressure  $p_s$  is fundamental to control the actuator output force  $f_p$  [36]; see Fig. 3a. As Watton [22] showed, the steady-state chamber pressures of single-DOF hydraulic cylinders are complex nonlinear functions of supply pressure, load force, friction force, motion direction and valve opening, even if servovalve leakage flow is neglected. With a typical hydraulic cylinder control in Fig. 3a, a single control valve is used to control the actuator output force (and motion). This allows only the control of the actuator output force  $f_{p1}$  ( $f_{p1} = A_{a1}p_{a1} - A_{b1}p_{b1}$ ), where  $A_{a1}$  and  $A_{b1}$  denote the piston areas at both chambers) while individual chamber pressures  $p_{a1}$  and  $p_{b1}$  are not controllable. This is a consequence of the typical control valve structure where the meter-in and meter-out orifices are mechanically coupled (with a spool), thus disabling the individual control of the chamber pressures.

For simplicity, consider that a piston of the first actuator is moving left in Fig. 3a. Let the fluid flow rates in the cylinder chamber be written as  $Q_{a1}$  and  $Q_{b1}$ . The power loss in the control valve 1 can be written as  $P_{loss} = |Q_{a1}|(p_s - p_{a1}) + |Q_{b1}|(p_{b1} - p_t)$ . Then, the hydraulic energy loss  $E_{loss}$  in the

<sup>3</sup>In displacement control, a hydraulic actuator is controlled directly with a discharged fluid flow rate of the pump by varying the pump’s geometrical displacement volume (a swash plate angle with a variable displacement axial piston pump). With EHAs, an actuator is controlled via a fixed displacement pump with speed variation using an electric motor.

<sup>4</sup>Among VDPs, the variable displacement axial piston pump (VDAPP) is the most widely used. In this paper, VDP refers to a VDAPP.

control valve 1 is  $E_{loss} = \int_0^t P_{loss}(\tau) d\tau$ . With high fluid flow rates ( $Q_{a1}$  and  $Q_{b1}$ ) and uncontrollable chamber pressures ( $p_{a1}$  and  $p_{b1}$ ), substantial energy losses can occur in the system.

In high flow applications, separate 3-way valves are used for each cylinder port (see Fig. 3b) since huge flow forces acting on the valve spools and meter-in/meter-out pressure losses make the use of 4-way servovalves (Fig. 3a) impractical. This concept is called separate-meter-in-separate-meter-out (SMISMO) control (see [107] and [108]) and a few companies have developed components targeted to mobile working machine applications (see [109] and references therein). The need for this more flexible control is justified in situations when 1) high flow rates occur, 2) there is the possibility for over-running load or 3) the individual cylinder chamber pressures are needed to be controlled.

Fig. 3b shows the operational principles for SMISMO control. Now, both cylinder chambers can be individually controlled, although the actuator output force is still coupled to the chambers pressures. Theoretically, the actuator output force can now be generated with an infinite number of chamber pressure ( $p_{a1}$  and  $p_{b1}$ ) combinations. To reduce the actuator energy consumption, the objective is to realize the needed output force with the combination of the lowest possible pressure levels. However, realization of an accurate chamber pressure tracking control is not an easy task. This is due to the highly nonlinear dynamic behaviour of hydraulic actuators (see Section I) which makes the cylinder chamber pressure control non-trivial and challenging. In addition, some pressure margins must be left in the lowest chamber pressure level so that cavitation is avoided. It is valid to mention that *if one pump is used for multiple actuators, the highest pressure level in the actuators' chambers defines the discharge pressure  $p_s$* ; see Fig. 3b.

Studies on SMISMO control of  $n$ -DOF hydraulic manipulators have been reported in [36], [44], [47], [110]. The challenges in chamber pressure tracking can be seen in experimental results in [36] and [44], where chamber pressure tracking errors up to 0.4 MPa occurred (with a hydraulic manipulator). Thus, more accurate control designs are needed for an implementation of SMISMO control in hydraulic manipulators.

The goal of SMISMO control is to lower the actuator(s) chamber pressure levels ( $p_{a1}$  and  $p_{b1}$ ) so that the system discharge pressure  $p_s$  can be lowered, i.e.,  $p_s = \max(p_{1a}, p_{1b}) + \Delta p_c$ , where  $\Delta p_c$  is a constant pressure margin across the control valve (typically 0.5–2 MPa). This will lead to a lowered system energy consumption (the hydraulic energy supplied to the system is  $E = \int_0^t Q_p(\tau) p_s(\tau) d\tau$ ), *if an advanced control is used for the hydraulic power supply, i.e., the hydraulic pump*. This will be discussed next.

### B. Energy-Efficient Control of Hydraulic Power Supplies

Commercial state-of-the-art hydraulic mobile manipulators are still controlled manually by controlling each actuator separately via visual feedback. Such systems are relatively energy efficient since they utilize pressure-compensated over-center proportional control valves combined with VDP's hydro-mechanical control to enable low stand-by energy consumption when the manipulator motion is stopped. Moreover, some advanced start–stop systems are available. It should be noted that

a similar system is quite difficult to achieve in high performance critically-lapped servovalve systems that either need separate lock-valves or counter-balance valves for the stop state. These safety functions are often a legislative requirement for commercial product certification, and thus are seldom addressed by academic research, although there are a few exceptions [111], [112]. For energy efficiency, commercial mobile manipulators commonly use the load sensing (LS) (e.g., [113]–[116]) principle where the highest driven actuator load pressure is fed back to VDP's hydro-mechanical controller, which sets the pump supply pressure slightly above the highest load pressure. Similar to the above mentioned  $\Delta p_c$ , this value is called the LS  $\Delta p$ -value ranging typically from 0.5–2 MPa. LS systems are quite effective in commercial open-loop controlled systems, especially if they have evenly distributed loading in each actuator. However, for servocontrol, LS application is not easy since the load dynamics and the VDP dynamics become heavily coupled through the VDP's hydro-mechanical feedback system. Thus, LS systems are well known for their oscillatory or even unstable behaviour [113]–[115].

Therefore, several studies for controlling the discharge pressure with the electro-hydraulically controlled VDP (e.g., [117]–[119]) have been carried out. Similar to the LS principle, the control objective is to make the pump discharge pressure track the highest driven load pressure. However, this is realized by using an electro-hydraulic control valve (to control VDP's swash plate), instead of using a hydro-mechanical LS mechanism, and designing a supply pressure tracking controller for VDP. The mapping between the VDP supply pressure and the electro-hydraulic control valve input is very complex, governed by a highly nonlinear fourth-order differential equation [120], making the control design task extremely challenging. This difficulty in control design has prevented the realization of full-model-based nonlinear control, forcing the use of either linearization or model-reduction methods.

Other solutions to control the hydraulic power supply exist as well. One feasible solution is to use a constant displacement pump with an angular velocity controlled (electric) motor [121]. Although this solution can substantially simplify system dynamics and control, the control of the input shaft angular velocity with required high acceleration times can lead to conservative and large servomotor sizing, which might not always be feasible. In addition, with this method, the dynamic response would be at least four times slower compared with the responses of the VDP [121].

One promising method for hydraulic power supply control has been digital hydraulic pumps [122]–[125]. With this method, a substantial potential for reducing system energy consumption has been reported. In addition, there are possibilities for energy recuperation and regeneration.

Typically, the simplest and cost-effective solution is to use a single VDP for multiple-actuator systems. However, a multiple-pump system can be used (with or without control valves), where each actuator has its own pump (see dashed lines and dimmed pump in Fig. 3). This technology is used in non-cost-driven aircraft systems where a high degree of reliability and even triple-redundant fault tolerance is achieved with the highly integrated EHAs [126], [127].

#### IV. FUTURE TRENDS AND OPEN PROBLEMS IN $n$ -DOF APPLICATIONS

Original Equipment Manufacturers (OEMs) of heavy-duty hydraulic mobile working machines (such as machines in construction, forestry, mining and material handling) are part of a huge global industry, with production currently limited to open-loop operator-controlled machinery. Similar to the car industry, these working machine OEM's are currently investing heavily into research and development towards more advanced machine control systems for increased machine productivity and to lessen operator burden and skill requirements. As mentioned, precursors to the trend towards autonomous and intelligent working machines can already be seen in commercial products (Sandvik AutoMine® [13] and John Deere IBC [14]).

Clearly, one of the key challenges that working machine OEMs in semi-autonomous machine design are facing is to produce machines that have as high level of performance and productivity as current commercial machines have with increased energy efficiency. The design requirements for new high-performance and energy-efficient hydraulic or hybrid actuation systems are moving towards downsizing the on-board power pack (e.g. diesel engine) to reduce emissions. However, actuators still have to have small enough volumetric dimensions and weight for maintaining the required working machine mobility. Needless to say, high-impact academic research should feed into this global robotization trend with replicable and measurable control design solutions that meet high performance requirements for robotic machines with several DOF's without introducing deterioration in energy efficiency.

As discussed in this paper, control of hydraulic actuators is still a challenge and it has not yet reached a commercial off-the-shelf level of maturity. However, e.g., embedded trajectory tracking controllers (as well as integrated power circuits and communication interfaces) make the electrical servo drives a commercial off-the-shelf solution for the robotics industries, regardless of their complexities and limitations [128]. In contrast with the challenges of stall torque of the electrical servo drives, hydraulic actuators are more suitable to generate impulsive motions. Moreover, hydraulic actuators can be direct-drive for linear or rotary motions of heavy payloads. Therefore, they can add key advantages to the robotic industry and significantly improve its impact. *Beyond currently available commercial state-of-the-art PID or state feedback controllers for single hydraulic axis motion/force controllers, there will be a broader market for truly intelligent integrated hydraulic actuators with embedded servo controllers and sensors that receive actuator-level commands through the fieldbus/network.* In the near future, these developments can pave the way for further advances in the field of hydraulic actuators too.

Hydraulically actuated humanoid robots and quadruped robots [4]–[7], [9]–[11], [91] have already been developed. Operations with these systems are becoming increasingly complex and more advanced control solutions are needed. As Tables I–III show, stability-guaranteed NMBC methods provide the most advanced control performance for the highly nonlinear hydraulic systems. Typical NMBC designs (as introduced in many books on the control of robots) are based on the

*Lagrangian dynamics* models of robots. With these methods, the complexity (computational burden) of robot dynamics is proportional to the fourth power of the number of DOFs of motion [52]. For a system with more than thirty DOF of motion (such as a humanoid robot), it is very difficult, if not impossible, to implement complete-dynamics-based control due to the computational burden. In fact, recently an increasing number of papers have reported on the phenomena called “explosion of complexity” even in relatively low order systems [129]. The offered solution to this backstepping method problem is design of observer-based dynamic surface controls to reduce this controller implementation problem [129]–[131].

*It can be expected that new subsystem-dynamics-based control design methods, based on the Newton-Euler dynamics (such as VDC [51], [52]), will gain more popularity.* With VDC the control computations are proportional to the number of subsystems (not to the fourth power of the number of DOFs of motion). As witnessed by Tables I and II, the subsystem-dynamics-based VDC can provide superior control performance (see [19], [43] and [45]). Furthermore, VDC also enables other very attractive features, such as: 1) the dynamics of each subsystem can be handled by decentralized controllers, while the central controller can focus on the kinematic computations [21], 2) subsystem dynamics remain relatively simple with fixed dynamic structures invariant to the target system, 3) changing the control (or dynamics) of a subsystem does not affect the control equations within the rest of the system, 4) adaptive control can be designed for the uncertain parameters involved in subsystem dynamics and 5) system stability analysis can be addressed at the subsystem level.

For robotic systems, energy efficiency cannot be designed at the expense of control performance. For hydraulic manipulators, energy efficient and high-performance closed-loop control (with guaranteed stability) is still an open problem. When moving toward more advanced hydraulic robotic systems, the system energy consumption becomes increasingly important as energy source(s) must be carried on board. Furthermore, stability-guaranteed NMBC is still an open problem for these systems. *So to sum up, the ultimate challenge is to achieve both energy efficiency and high-performance control (with guaranteed stability) for advanced hydraulic robotic systems.*

#### V. CONCLUSIONS

In this paper, an extensive literature survey on the control of hydraulic robotic manipulators was presented. Both serial and parallel manipulators were covered. For an objective evaluation of the state of the art and effectiveness of different methods (the cornerstones of scientific research and progress), a normalizing performance indicator  $\rho$  (the ratio of the maximum position tracking error with respect to the maximum velocity) was used to benchmark different methods in the literature for free-space motion control of hydraulic manipulators. It was found that the stability-guaranteed NMBC designs have resulted in the most advanced control performance, thus justifying their more complex control design procedure. It is strongly recommended to take a step toward more unified and effective evaluation methods in the robotics community. This paper promotes the performance indicator  $\rho$  in Section II-A3

to highlight the key specifications of the contemporary methods and achievements in future research contributions.

Given the problem, stability-guaranteed NMBC design for hydraulic robotic manipulators have faced a formidable challenge regarding free-space motions alone. In constrained motion control, NMBC methods are even more rare for hydraulic manipulators; only one stability-guaranteed NMBC design [94], which covers both free-space and constrained motions, has been proposed.

As mentioned, normalized performance indicators similar to  $\rho$  in (1) have not been reported to evaluate control performance of different contact force control methods. Development of such indicators is highly needed to promote reproducibility and measurable robotic research as discussed in [18].

Fundamental challenges for hydraulic robotic systems were identified as: 1) The dynamic behaviour of hydraulic systems is highly nonlinear, making their control, especially in constrained motions, a truly challenging task, and 2) traditional hydraulic systems are energy inefficient. Despite an importance to address the above challenges and their reciprocal contradiction (see Section III), energy-efficient and stability-guaranteed (high-performance) NMBC is still an open problem for hydraulic manipulators. An ultimate goal is to achieve both objectives for more complex hydraulic robotic systems, such as humanoids.

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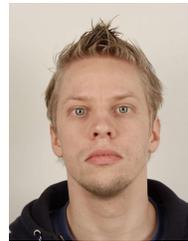
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