Additive Manufacturing for Agile Legged Robots with Hydraulic Actuation

Claudio Semini*, Jake Goldsmith*, Diego Manfredi†, Flaviana Calignano†, Elisa Paola Ambrosio†, Jukka Pakkanen†, Darwin G. Caldwell*

* Dept. of Advanced Robotics,
Istituto Italiano di Tecnologia (IIT),
via Morego, 30, 16163 Genova, Italy
`<first name>.<last name>@iit.it`

† Center for Space Human Robotics @Polito
Istituto Italiano di Tecnologia (IIT),
Corso Trento, 21, 10129 Torino, Italy
`<first name>.<last name>@iit.it`

***Abstract*—Agile and versatile legged robots are expected to become useful machines for applications in unstructured environments where traditional vehicles with wheels and tracks cannot go. Hydraulic actuation has proven to be a suitable actuation technology due to its high power density, robustness against impacts and high stiffness for high bandwidth control. In this paper we demonstrate how additive manufacturing (AM) can produce highly integrated hydraulic components with reduced weight and higher complexity when compared to traditionally manufactured manifolds. To the best knowledge of the authors, this is the first time a successful implementation of direct metal laser sintering (DMLS) of hydraulic manifolds made in aluminium alloy AlSiMg is presented. AlSiMg has several advantages for the construction of hydraulic components when compared to the commonly used Titanium alloys (e.g. Ti64): lower cost, higher thermal conductivity, lower density and easier to post-process. This paper first explains the build process with DMLS of AlSiMg and a pre-study of a pressure-tested hydraulic tube that demonstrated the suitability of AlSiMg for AM hydraulic components. Then, we discuss part orientation and support material during the build process of a highly-integrated hydraulic manifold for the legs of IIT's new hydraulic quadruped robot *HyQ2Max*. A comparison of this manifold with a traditionally manufactured alternative concludes the paper.**

I. Introduction

Research into legged robots is expected to result in vehicles that are able to navigate with agility on rough terrain, exceeding the mobility of wheeled and tracked vehicles. However, despite the efforts of several decades of research into legged robots the current state of the art is still far from reaching this goal. Recently a class of larger-sized, hydraulically actuated and torque-controlled quadrupedal robots (e.g. Boston Dynamics' *LS3* and *BigDog* [1] and IIT's *HyQ* [2]) have shown promising results of stable navigation over flat and rough terrain and in presence of lateral disturbances [3]. Such robots are expected to assist humans for practical applications such as search and rescue, fire-fighting, forestry and inspection/maintenance tasks in dangerous areas or where automation is required in unstructured environments.

Fundamental capabilities that such robots will need to have are the following: dynamic locomotion over rough terrain, dynamic balancing after disturbances, *self-righting* (to get back up on the feet after falling), active or passive compliance in the legs, state estimation and perception. To successfully implement these capabilities, the mechanical structure of the robot needs to have structural robustness to falls and impacts, and a light-weight and compact design. The actuation system needs to be controllable in torque, able to cope with impacts on the joints (e.g. during running and jumping) and provide high torque and velocity output with a high power density. Hydraulic actuation meets these requirements as we have demonstrated in our previous work [2], [4], [3], [5].

This paper addresses the requirement for a light-weight and compact design of the hydraulic actuation systems of agile legged robots. We demonstrate how additive manufacturing (AM) can produce highly integrated hydraulic components with reduced weight and higher complexity when compared to traditional manifolds.

Traditionally manufactured mechanical parts are usually produced by milling machines, lathes, electric discharge machining, laser cutting and casting. Most hydraulic manifolds are produced that way. Internal flow paths are created with a combination of holes that are drilled from the different faces of the manifold block. Auxiliary holes for internal flow paths that do not need to connect to the outside are sealed with grub screws. This technique has several drawbacks: First, it reduces the freedom of the designer to build compact manifolds because all the different flow paths need to be separated by a certain safety distance (depending on pressures and material). Second, it often results in sharp 90° bends that lead to pressure loss, heat and increased risk for cavitation.

In recent years, a few researchers have started to use AM to produce smarter manifolds that overcome the above-mentioned drawbacks. Among the various AM technologies, in Selective Laser Melting (SLM) a high power laser is used to melt a powder feedstock to form fully dense metallic parts, which are fit for end-user products. The use of SLM gives design and manufacturing freedom without the restrictions of traditional machining processes. This leads to lighter components, better integration and for hydraulic components, the ability to enhance internal flow paths, thus greatly improving the flow characteristics [6].

978-1-4673-7509-2/15/$31.00 2015 IEEE

While titanium and steel are widely used materials for AM parts, aluminium alloys have been less popular for various reasons, including difficulties related to the high reflectivity and high thermal conductivity of Al powders, that reduce the powder's heat absorption capacity. However, there is a large potential for AM with aluminium alloys especially for hydraulic components, since it has several advantages over titanium: (1) Lower cost: aluminium alloy powders (e.g. AlSiMg) are on average around 4 times cheaper than titanium powder (e.g. Ti6Al4V); (2) higher thermal conductivity [7] [8]: AlSiMg has a thermal conductivity of 103-119W/mK [7][9], compared to 6-7W/mK of Ti6Al4V [10]. It is therefore very suitable for hydraulic components, since it helps to dissipate heat in a distributed manner; (3) lower theoretical density: AlSiMg has 2.68 g/cm^3 [10], [11] vs. 4.41 g/cm^3 in the case of Titanium Ti64 [12]; (4) easier to post-process, e.g. for adding threads.

This paper describes how direct metal laser sintering (DMLS), tradename of EOS for SLM, of aluminium alloys is used to fabricate compact hydraulic manifolds of IIT's new Hydraulic Quadruped *HyQ2Max*. We explain in detail how to manufacture and post-process the parts. Furthermore, we show how the more compact design can save weight and space, and helps to create a highly integrated hydraulic distribution system for the quadruped robot's legs. We then compare a traditionally manufactured part with the new AM part to assess the weight reduction.

The contributions of this paper are the following: To the best knowledge of the authors, this is the first time aluminium alloy has been successfully used for the production of AM hydraulic manifolds. The clear advantages of aluminium alloy (low cost, high thermal conducitvity, low density, good for post-processing) makes it a promising alternative to the commonly used titanium. Futhermore, this paper presents a novel highly-integrated hydraulic manifold for an agile legged robot, where light-weight and compact hydraulic components are crucial.

This paper is structured as follows: Section II describes the related work. Section III gives a brief overview of the new quadruped robot HyQ2Max with a focus on its hydraulic actuation system. Section IV explains the manufacturing process of SLM and Section V present a pre-study that analyses a hydraulic tube that was manufactured with this process. Next, Section VI shows the design of a highly integrated hydraulic manifold for the legs of HyQ2Max and a study on the part orientation and support material. Section VII shows a weight comparison between the AM manifold and a traditionally manufactured alternative, and Section VIII draws the conclusions of this work.

II. Related Work

Additive manufacturing has been widely used in the production of legged robots. The vast majority is made with rapid prototyping in plastic. This section will therefore focus on AM of metal parts applied to high-pressure hydraulic actuation. To the best knowledge of the authors, no scientific publications exist in the field of robotics. Therefore, this section reports on studies in the fields of motor sport and automotive industry.

Cooper *et al.* [6] showed how DMLS is used for the production of hydraulic components in Formula 1 racing. The authors used EOS Titanium Ti64 material to test parts of different geometries and wall thickness. They concluded that even thin-walled (0.5mm) hydraulic component resist the demanding conditions of motor sport applications. Furthermore, they showed that the DMLS manufactured geometry has improved the flow characteristics by 250% over that of the currently used techniques of manufacturing channels and bores.

Hufenbach *et al.* [13] investigated the weight-saving potential of AM hydraulic manifolds for the automotive industry. They show how an AM steel manifold can reduce the weight by over 50% compared to a reference manifold in mono-block design.

In another study [14], AM with titanium was used to optimise a traditional aluminium block manifold, leading to a weight reduction of 72%.

Brookes reported in [15] that the company *3T RPD Ltd.* has developed a hydraulic manifold made from 15-5PH stainless steel by DMLS. He writes that smoothly curved tubes are built inside the lightweight block, just 40% of the weight of the previous solid design.

The EU project *COMPOLIGHT* (2008-2011, led by Jay Olivier) has resulted in several interesting studies about AM-manufactured hydraulic manifolds. Unfortunately, no scientific publication is available. Only a few brochures on the project website[1]. The brochures show examples of AM applied to hydraulic manifolds, e.g. for a pump for a plastic extrusion machine. The studies resulted in significant weight reductions.

The group of Dr. Lonnie Love at the Oak Ridge National Laboratory (USA) studies AM metal parts applied to robotics, as for example a fluidic hand made of titanium. Unfortunately, no scientific publications are availble about this work. We refer the interested reader to the group's website [2].

III. HyQ2Max Robot Design

This section gives a short overview of the design of IIT's new Hydraulic Quadruped robot HyQ2Max [16] (see Fig. 1), whose development is based on 7 years of experience with the HyQ robot[3] [2], [17] and leg prototypes [18].

A. Robot Design Overview

Figure 1 shows a CAD model of the robot with the main design features. The robot weighs 80kg with offboard hydraulic power supply and is around 1.2m long and 0.9m high with fully extended legs. All joints have high-resolution position and torque sensing; and are powered by hydraulic actuation.

[1] http://compolight.dti.dk/
[2] http://web.ornl.gov/sci/manufacturing/research/additive/
[3] info and videos on http://www.iit.it/hyq

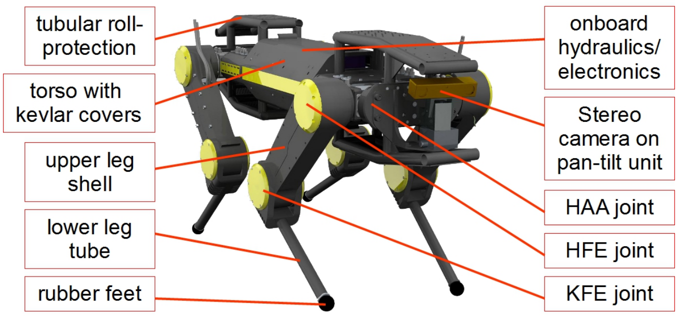


Fig. 1. CAD rendering of the quadruped robot HyQ2Max with explanation of the main design features. Each leg consists of 3 joints: Hip Abduction/Adduction (HAA), Hip Flexion/Extension (HFE) and Knee Flexion/Extension (KFE).

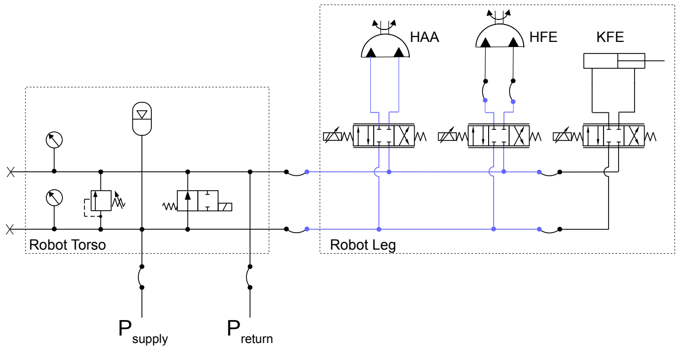


Fig. 2. Schematics of the hydraulic actuation system of the HyQ2Max quadruped robot. All flow paths marked in blue are inside the AM manifold presented in this paper.

HyQ2Max has the following enhanced features over HyQ:

- extended range of motion (allows self-righting)
- higher joint torques (for faster motions, higher payload)
- higher robustness (against impacts, dirt, water)

The real-time control software with EtherCAT communication allows position and torque control in all the joints at 1kHz. Torque control is a crucial element for an agile and versatile robot that has to navigate in an unstructured and dynamically changing environment.

B. Hydraulic Actuation System

The robot uses a combination of hydraulic cylinders and rotary vane actuators that are controlled with high-performance servovalves (MOOG E024 [19]). Hydraulic actuation was selected for this robot due to its high power density, robustness against impacts and high stiffness for high bandwidth control.

Figure 2 shows the schematics of the onboard hydraulic system. Only one leg is illustrated as all four legs have identical hydraulic components. The HAA and HFE joints are actuated by rotary vane actuators. The KFE joint is powered by a hydraulic cylinder. The figure indicates in blue which hydraulic flow paths are implemented in the hydraulic leg manifold that is presented in Section VI. A compact and light-weight design of the manifold is crucial for the integration into an agile legged robot.

IV. Manufacturing Process of Aluminium Alloy Parts with Selective Laser Melting

Recent developments in rapid manufacturing, as the application of modern fiber laser beam sources, enable the so-called additive manufacturing (AM) technologies to substitute conventional manufacturing processes: these technologies allow to build near-net shape components, one layer at a time, using data directly from 3D CAD models. The main benefits can be summarized in reducing component lead time, material waste, energy usage, and carbon footprint. In this regard, Selective Laser Melting (SLM) shows a large annual market growth and gradually gains influence in manufacturing and production technology. In SLM a high energy laser source is used to melt powders to form layer by layer fully dense metallic parts. Therefore it is possible to design internal features and passages that could not be cast or otherwise machined. Complex geometries and assemblies with multiple components can be simplified to fewer parts and less assembly costs. Applications using this technology include direct parts for a variety of industries including aerospace and other industries that use complex parts of small to medium size for short production runs. However currently there are no design guidelines for additive manufactured components, and in particular only few examples of hydraulic parts.

The basic procedural principles of the different one-step SLM processes, e.g. *Selective Laser Melting* of *SLM Solutions GmbH*, of *ReaLizer*, of *Renishaw plc*, *Direct Metal Laser Sintering* of *EOS GmbH*, *LaserCUSING* of *Concept Laser GmbH*, are almost identical: a focused laser beam is deflected with velocities up to 3.0 m/s to solidify a metal powder, processing a layer thickness between 20 and 60 μm. However, significant differences can be observed in the materials and within the individual process and scanning strategies of this technology: SLM is a complex process, giving rise to a multitude of physical phenomena [20], [21]. Therefore, even though the SLM process involves the complete melting of the fine metal powder, the final properties of the SLM part are very different from that of the parts produced by conventional method such as casting or die casting. In SLM technology, densification mechanism, roughness, microstructure and mechanical properties are strongly influenced by processing parameters and by powders properties. The main process parameters that can determine the quality of a component are: laser power and laser type, scan rates, atmospheric control, scanning strategy, heaters (bed temperature), layer thickness, building directions, and post process treatments. Hence to be confident about designing with this technological process and the selected material, it is fundamental to evaluate the effect of the specific processing machine's parameter settings on the surface and microstructural/mechanical properties of the final components.

In this study an *EOSINT M270 Xtended* machine was employed. The machine uses a 200W Yb fiber continuous laser beam with wavelength of 1060-1100 nm. The focused diame-

TABLE I
CHEMICAL COMPOSITION OF EOS ALSI10MG ALLOY POWDER IN ACCORDANCE WITH STANDARD DIN EN 1706:2010-06

Element	Si	Fe	Cu	Mn	Mg	Zn	Ti	Al
Weight [%]	9-11	0.55	0.05	0.45	0.2-0.45	0.1	0.15	remainder

TABLE II
PHYSICAL AND MECHANICAL PROPERTIES OF THE ALSIMG ALLOY AFTER DMLS PROCESS AND STRESS RELIEVING HEAT TREATMENT.

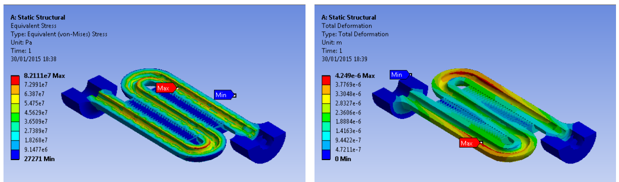
Theoretical Density (g/cm^3)	Geometric Density (g/cm^3)	Residual Porosity (%)	Hardness (HV)	Youngs Modulus E (GPa)	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation at break (%)
2.68	2.66	0.8	106 ± 5	73 ± 1	240 ± 8	350 ± 6	6.5 ± 0.5

ter of the laser beam is 0.1 mm, with a maximum scan speed of 7000 mm/s. The building volume of the machine is 250 mm x 250 mm x 215 mm. Previous studies of the authors describe a complete characterization of AlSi10Mg alloy by DMLS and the adopted, optimized process parameters [22], [23], [11]. In comparison to a commercial as-cast A360 alloy, with a similar chemical composition, DMLS specimens demonstrated very high values of ultimate tensile strength and yield strength, due to the very fine microstructures that arise from this process. Moreover, in [24], Calignano performed a detailed study on the possible way to determine the best orientation inside the SLM chamber to build a complex part in aluminium alloy, together with the minimum use of supports structure. In 3D printing and AM support structures have to hold unsupported geometries in place and to prevent distortion of the part during fabrication. The accuracy of a part and its manufacturability are related to the building orientation especially if the part has internal channels. Specifically with SLM, it is possible to insert support structures into the channels, however they are often undesired.

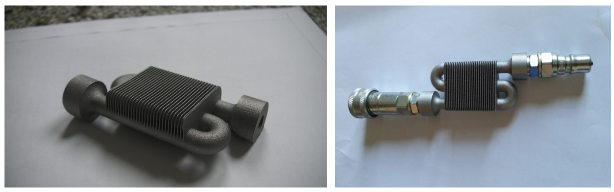
V. PRE-STUDY OF SLM HYDRAULIC LINE ELEMENT

For a pre-study of SLM hydraulic parts, we designed s-shaped hydraulic tubes (Fig. 3) with different wall thicknesses. We analysed the strength of the design with a numerical Finite Element Model (FEM) of the part by testing the mechanical stress under 40MPa of hydraulic pressure inside the tube, which is double the maximum operating pressure of 20MPa. Figure 3 (top) illustrates the von-Mises stress and displacement of the tube with a wall thickness of 3mm. The maximum stress is 82Mpa, which is well inside the yield strength of the material (see Table II).

Two identical copies of the tubes (Fig. 3 bottom) were fabricated at IIT in an aluminium powder (AlSi10Mg by EOS, see Table I and II) through DMLS. After stress relieving and detachment from the building platform, the parts were subjected to shot-peening post processing. It was demonstrated that shot-peening is effective to modify the surface roughness on open areas of the part [22], but it was not clear yet whether it is effective also inside cavities and channels. One of the two parts was then pressure-tested for several hours with hydraulic flow rates of up to 15 liters per minute and under static pressure tests with 20MPa. Afterwards, both hydraulic tubes were cut in half and examined with a *Leica EZ4D* stereomicroscope and with a *SM Instruments RTP 80* Roughness tester. In any case, the shot-peening post treatment is fundamental to remove the loose powder, also from the internal channels, that could be detrimental for hydraulic actuation (e.g. the high-performance servovalves used in this paper are susceptible to oil contamination, requiring oil contamination levels of NAS 3 or below [19]). The section of the tube just after the shot peening is shown in Fig. 3(b) on the left, with tags numbering the 3 different areas analysed with the stereomicroscope. The section of the second tube, which has been pressure tested with oil, is shown in Fig. 3(b) on the right. The same areas as indicated in Fig. 3(a) were analyzed by the stereomicroscope.



(a)



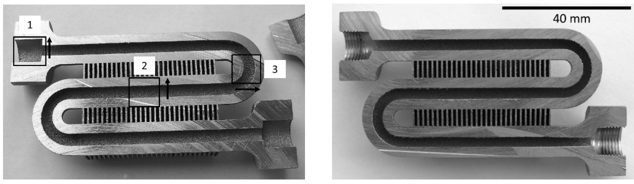
(b)

Fig. 3. S-shaped aluminium tubes made by Direct Metal Laser Sintering (DMLS): (a) results of *ANSYS* FEM analysis, illustrating von-Mises stress and displacement at 40MPa of static hydraulic pressure inside the tube; (b) pictures of the tube just after shot-peening (on the left), and after pressure testing with oil (on the right).

The first fundamental observation is that the internal channel shape is exactly as designed. No visual geometric deformation happened during the manufacturing.

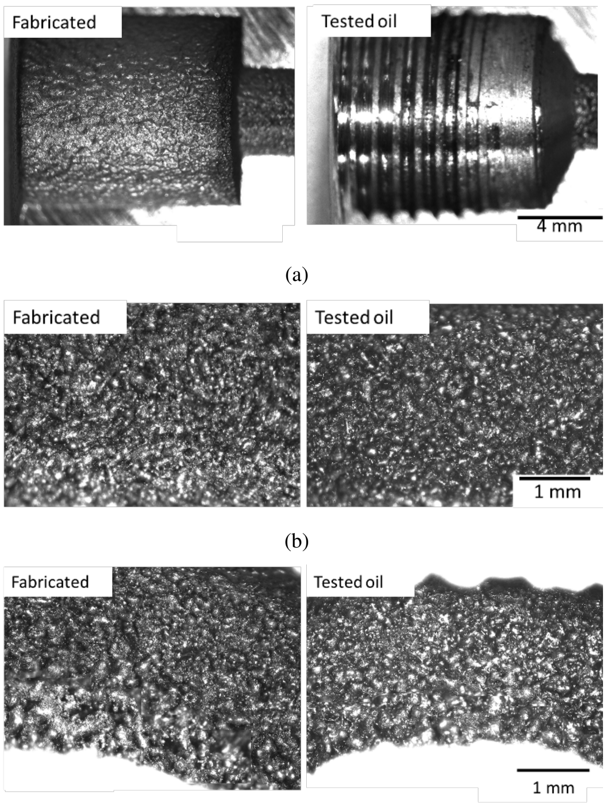
Figure 5(a) shows area 1, which is an inside cavity of the manifolds that is accessible with shot peening. The picture on the right shows the same surface that was machined to produce the threads for hydraulic connectors.

The inside channel of the tubes did not show visual differences: the fabricated part and the oil-pressure tested part look similar under the stereomicroscope. The comparison is



(a) (b)

Fig. 4. S-shaped aluminium tube cut open. (a) Section of the part that was not tested in oil. Tags show the areas that were examined by the stereomicroscope: 1. Fixing cavity, 2. Inside channel and 3. Curve. (b) Section of the part that was used for pressure testing.



(c)

Fig. 5. Stereomicroscope analysis of the cut-open hydraulic tubes after shot peening (on the left) and tested with oil (on the right). (a) Inside cavity reachable with shot peening and machined with threads (area 1 as indicated in Fig. 4(a)); (b) Inside channel of the manifolds (area 2); (c) Corner section of the manifolds (area 3).

shown for the three areas defined above. Figure 5(b) shows the area 2 and Fig. 5(c) the surface inside a curve (area 3). In order to quantify the differences, if any, between the fabricated part and the oil-pressure tested part, we calculated the Average Roughness, Ra, that measures the average length between the peaks and valleys and the deviation from the mean line on the entire surface within the sampling length, and the Mean Roughness Depth, Rz, calculated as arithmetic mean of the vertical distance from the highest peak to the lowest valley within five sampling lengths. The values obtained are Ra of 21.41 μm and Rz of 98.02 μm for the fabricated part, and Ra of 20.87 μm and Rz of 97.41 μm for the oil-pressure tested part. Therefore, we can conclude that after testing with pressurized oil, the inner surface of the s-shaped tube sample does not exhibit any modifications or degradation.

VI. SLM Hydraulic Manifold for HyQ2Max Legs

After the successful pre-study presented in the previous section, we designed a manifold for the legs of HyQ2Max. This section will first explain the function of the manifold and its location on the robot. Then, it will present a study on the support material location and part orientation.

A. Hydraulic Leg Manifold Design

Each leg of the HyQ2Max robot has three hydraulic actuators that need to be supplied with hydraulic fluid through a pressure supply and return line. To reduce the weight and complexity of the robot, the number of hydraulic pipes and hoses has to be minimal. Furthermore, the majority of the mass of the legs of agile legged robots has to be as close to the body as possible to reduce the leg inertia (to reduce torque requirements during swing phase and impact forces during touch-down) [17].

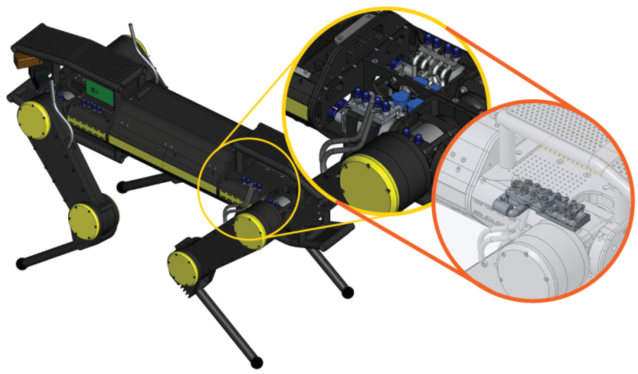


Fig. 6. CAD model of HyQ2Max with close-up views of the highly-integrated hydraulic manifolds of the two hind legs.

For these reasons we designed a highly-integrated hydraulic manifold that is located inside the robot torso as illustrated in Fig. 6. The manifold has several functions:

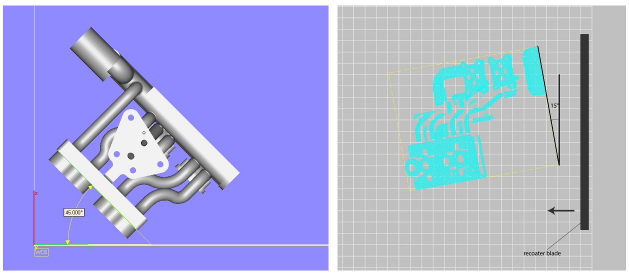
- manifold for the servovalves of the HAA and HFE joints,
- direct hydraulic connection of HAA servovalve control ports to HAA rotary vane motor,
- relay of pressure supply and return lines for the KFE cylinder.

The AM manifold was then produced according to the procedure explained in Section IV. To achieve the desired manufacturing results, the part orientation and usage of support material has to be carefully studied as explained next.

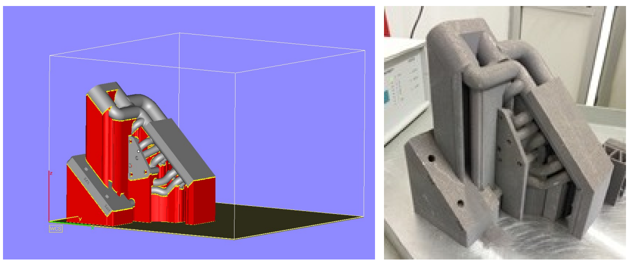
B. Study on Part Orientation and Support Structures

To maintain the accuracy of the geometric shape of the channels and avoid distortions, it would be necessary to insert support structures. But due to the impossibility to remove these supports in internal closed regions, it is fundamental to find the right orientation of the channels to be self-standing. In this way the channel can be considered such as an overhanging structure, that is a part of a component that is not supported during building by solidified material or a substrate on the bottom side. By analyzing the limits of construction of the overhanging structures, it is possible to determine the areas that require support structures and then derive the optimal orientation. According to the experiment on self-supporting structures [24], overhanging surfaces inclined at angles less than 30° require supports, while surfaces with angles between 45° and 30° are self-supported. Although the best positions are parallel or vertical angles relative to the building platform, unfortunately these two positions do not always make it possible to build parts of complex geometry as for example objects with internal channels. Vertical channels are more accurate and have better circularity with respect to horizontal ones. In the horizontally fabricated channels, the layers of the top of the hollow are melted by the laser on loose powder material: therefore the so-called dross formation happens with a negative impact on the accuracy of the internal cavities. However, this problem can be solved by changing the geometry (e.g. ellipse instead of a circle) or the orientation of the part.

As can be seen in Fig. 7(a) on the left, the chosen orientation for the production of the hydraulic manifold and the support structures is 45°. Moreover, Fig. 7(a) on the right shows that the part was built with an angle of 15° between y axis and the recoater blade to prevent the deformation of the part. Figure 7(b) illustrates the use of support material.



(a)



(b)

Fig. 7. Part orientation and support material for the manufacturing of the hydraulic manifold. (a) CAD models of the hydraulic manifold illustrating the selected orientations for production. (b) Support structure used for the production of the hydraulic manifold: Left: CAD rendering illustrating the support material in red; Right: picture of manifold before post-processing.

The samples were then shot-peened (*Ecoblast/F machine*, by *Silco S.r.l., Italy*) to improve the surface quality and integrity [22]. In this study, zirconia beads in the range of 100-200 μm diameter with an air pressure value of 0.6MPa for several seconds were used. Figure 8 shows pictures of the manifolds after shot-peening and after post-machining for threads and surface polishing.

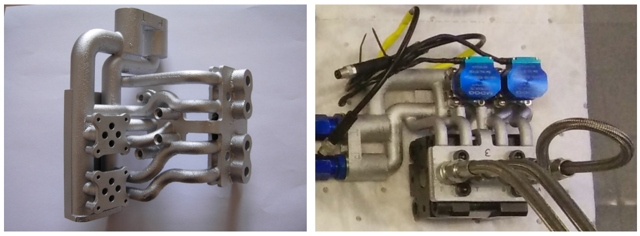


Fig. 8. Pictures of hydraulic manifold: *Left:* manifold after shot-peening; *Right:* manifold with hydraulic components after post-machining for threads and surface polishing. Two servo-valves, one rotary vane motor and hoses are mounted onto the manifold.

VII. Comparison between Milled and AM Hydraulic Manifolds

To assess the advantage of the AM produced manifold, we tried to design a traditionally manufactured part (e.g. by milling) with the same functionalities. As illustrated in Fig. 9 on the left, we did not manage to insert all required internal flow paths due to crossing channels (the pressure supply and return lines to the KFE cylinder are missing). Adding them would have significantly enlarged the part thickness, because flow paths in two different and separated planes would be required.

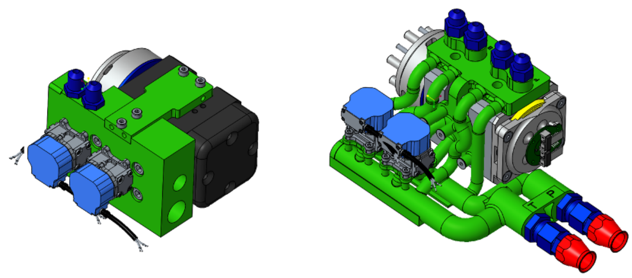


Fig. 9. CAD models of hydraulic manifolds for the legs of the HyQ2Max robot. *Left:* traditionally manufactured manifold (green parts). *Right:* highly integrated AM manifold.

We then compared the empty weight of the traditionally manufactured part (0.520kg, Fig. 9 on the left) with the AM part (0.313kg, Fig. 9 on the right). Even though the lines to the KFE cylinder were not present, the traditionally manufactured part weighs over 160% more than the AM part.

Furthermore, as shown in [6], the smoother bends inside the flow paths of AM manifolds result in less flow disturbance (thus smaller pressure drops) when compared to the sharp 90° bends inside the traditionally manufacutred part.

VIII. Conclusions

This paper presented a study on the use of additive manufacturing for hydraulic components of an agile legged robot with hydraulic actuation. We presented for the first time how direct metal laser sintering of aluminium alloy AlSi10Mg can be successfully used for highly integrated hydraulic manifolds. Aluminium has several advantages over titanium for this applications due to lower cost, better thermal conductivity, lower density and easier post-machining of threads. We have tested an AM hydraulic tube prototype inside a hydraulic circuit with pressures up to 20Mpa and analysed its internal surface with a stereomicroscope. No visual changes were identified, which allowed us to continue our research with the production of a highly integrated hydraulic manifold for the quadruped robot HyQ2Max. We show how AM manufacturing allows for compact and light-weight design by comparing the manifold with a traditionally manufactured part. We demonstrated the potential of AM aluminium alloy parts for hydraulic components in robotics and other fields where low weight and a high degree of integration is crucial.

Further studies will analyse how much material can be saved with thinner walls and focus on methods that reduce the need for post-processing.

References

[1] M. Raibert, K. Blankespoor, G. Nelson, R. Playter, and the BigDog Team, "Bigdog, the rough-terrain quadruped robot," in *Proceedings of the 17th World Congress The International Federation of Automatic Control (IFAC)*, 2008.

[2] C. Semini, N. G. Tsagarakis, E. Guglielmino, M. Focchi, F. Cannella, and D. G. Caldwell, "Design of HyQ - a hydraulically and electrically actuated quadruped robot," *Journal of Systems and Control Engineering*, vol. 225, no. 6, pp. 831–849, 2011.

[3] V. Barasuol, J. Buchli, C. Semini, M. Frigerio, E. R. De Pieri, and D. G. Caldwell, "A reactive controller framework for quadrupedal locomotion on challenging terrain," in *2013 IEEE International Conference on Robotics and Automation (ICRA)*, 2013.

[4] T. Boaventura, C. Semini, J. Buchli, M. Frigerio, M. Focchi, and D. G. Caldwell, "Dynamic torque control of a hydraulic quadruped robot," in *IEEE International Conference in Robotics and Automation*, 2012.

[5] C. Semini, V. Barasuol, T. Boaventura, M. Frigerio, M. Focchi, D. G. Caldwell, and J. Buchli, "Towards versatile legged robots through active impedance control," *The International Journal of Robotics Research (IJRR)*, 2015.

[6] D. Cooper, M. Stanford, K. Kibble, and G. Gibbons, "Additive manufacturing for product improvement at red bull technology," *Materials and Design*, vol. 41, pp. 226–230, 2012.

[7] L. Ventola, F. Robotti, M. Dialameh, F. Calignano, D. Manfredi, E. Chiavazzo, and P. Asinari, "Rough surfaces with enhanced heat transfer for electronics cooling by direct metal laser sintering," *International Journal of Heat and Mass Transfer*, vol. 75, pp. 58–74, 2014.

[8] E. Chiavazzo, L. Ventola, F. Calignano, D. Manfredi, and P. Asinari, "A sensor for direct measurement of small convective heat fluxes: Validation and application to micro-structured surfaces," *Experimental Thermal and Fluid Science*, vol. 55, pp. 42–53, 2014.

[9] EOS GmbH - Electro Optical Systems, *EOS Aluminium AlSi10Mg - Material data sheet*, 5 2014.

[10] ASM International the Materials Information Company, *Properties and Selection: Non ferrous Alloys and Special-Purpose Materials*, ASM Handbook, 1990.

[11] D. Manfredi, F. Calignano, M. Krishnan, R. Canali, E. P. Ambrosio, S. Biamino, D. Ugues, M. Pavese, and P. Fino, *Light Metal Alloys Applications*, 2014, ch. Additive Manufacturing of Al Alloys and Aluminium Matrix Composites (AMCs), pp. 3–34.

[12] EOS GmbH - Electro Optical Systems, *EOS Titanium Ti64 - Material data sheet*, 10 2011.

[13] W. Hufenbach, A. Ulbricht, D. Barfuss, M. Birke, B. Zhou, and K. Kunze, "Lightweight hydraulic components in novel multi-material-design for mobile applications," in *International Fluid Power Conference (ifk)*, 2014.

[14] M. Kausch, "Entwicklung hochbelasteter leichtbaustrukturen aus lasergenerierten metallischen komponenten mit faserverbundverstrkung," Ph.D. dissertation, Technical Univeristy of Chemnitz, 2013.

[15] K. J. A. Brookes, "PM AM at Farnborough," *Metal Powder Report*, vol. 69, no. 6, pp. 34–35, 2014.

[16] C. Semini, J. Goldsmith, B. U. Rehman, M. Frigerio, V. Barasuol, M. Focchi, and D. G. Caldwell, "Design overview of the hydraulic quadruped robots HyQ2Max and HyQ2Centaur," in *The Fourteenth Scandinavian International Conference on Fluid Power (SICFP)*, 2015.

[17] C. Semini, "HyQ – design and development of a hydraulically actuated quadruped robot," Ph.D. dissertation, Istituto Italiano di Tecnologia (IIT) and University of Genova, 2010.

[18] C. Semini, N. G. Tsagarakis, B. Vanderborght, Y. Yang, and D. G. Caldwell, "HyQ – hydraulically actuated quadruped robot: Hopping leg prototype," in *Proceedings of the IEEE International Conference on Biomedical Robotics and Biomechatronics (BioRob)*, 2008, pp. 593–599.

[19] MOOG Inc., *Data Sheet of E024 Series Microvalve*, 2003.

[20] A. Simchi, "Direct laser sintering of metal powders: Mechanism, kinetics and microstructural features," *Materials Science and Engineering: A*, vol. 428, pp. 148 – 158, 2006.

[21] J.-P. Kruth, G. Levy, F. Klocke, and T. Childs, "Consolidation phenomena in laser and powder-bed based layered manufacturing," {*CIRP*} *Annals - Manufacturing Technology*, vol. 56, no. 2, pp. 730 – 759, 2007.

[22] F. Calignano, D. Manfredi, E. Ambrosio, L. Iuliano, and P. Fino, "Influence of process parameters on surface roughness of aluminum parts produced by DMLS," *Int. J. Adv. Manuf. Tech.*, vol. 67, pp. 2743–2751, 2013.

[23] D. Manfredi, F. Calignano, M. Krishnan, R. Canali, E. Ambrosio, and E. Atzeni, "From powders to dense metal parts: Characterization of a commercial AlSiMg alloy processed through direct metal laser sintering," *Materials*, vol. 6, no. 3, pp. 856–869, 2013.

[24] F. Calignano, "Design optimization of supports for overhanging structures in aluminum and titanium alloys by selective laser melting," *Materials and Design*, vol. 64, pp. 2013–213, 2014.