DESIGN OVERVIEW OF THE HYDRAULIC QUADRUPED ROBOTS HyQ2MAX AND HyQ2CENTAUR

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ABSTRACT

Legged robots have not yet demonstrated the desired versatility and higher mobility that would justify their more complicated design with respect to wheeled or tracked vehicles. To make these robots ready for real world applications -- for example as assistants to humans in dangerous areas -- important challenges must be solved first, such as dynamic locomotion over rough terrain, dynamic balancing after disturbances, structural robustness to falls, *self-righting* (to get back up on the feet after falling), active or passive compliance in the legs, state estimation, perception and optional dexterous manipulation. In this paper we will focus on the robustness, self-righting and manipulation aspects. We will give an overview of the design of two new hydraulic robots: *HyQ2Max*, an improved, robust version of our hydraulic quadruped HyQ, and *HyQ2Centaur*, a centaur-style robot that combines the HyQ2Max locomotion platform with a pair of new hydraulic manipulator arms. We will focus on the self-righting ability of the quadruped robot and present the results of rigid-body dynamics simulations. Next, we will focus on the mechanical design concept of the new compact hydraulic arms and discuss the hydraulic actuation system. To the authors' best knowledge this is the first time the design of a fully hydraulically actuated centaur robot is presented.

KEYWORDS: hydraulic actuation, hydraulic centaur, quadruped, legged robot, mechanical design

1. 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 medium-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 agile 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, structural robustness to falls, *self-righting* (to get back up on the feet after falling), active or passive compliance in the legs, state estimation and perception.

The HyQ project of the Istituto Italiano di Tecnologia (IIT) started in 2007 and resulted in the first version of HyQ in 2011, a fully hydraulic, torque-controlled quadruped robot [2]. Since then, HyQ has demonstrated a wide repertoire of static and dynamic motions ranging from walking trot over flat, inclined and rough terrain (indoors and outdoors), balancing under disturbances [3], flying trot [4], squat jumps, step reflexes [5], perception-enhanced trotting and crawling [6][7], to an optimized crawl gait for walking on stairs and stepping stones [8]. A summary video of these results is available online [9].

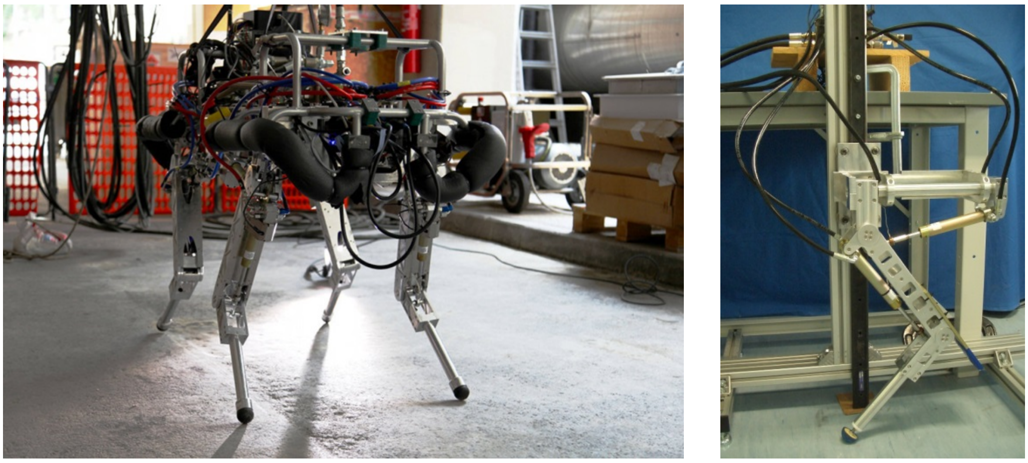

Figure 1. Pictures of the first version of HyQ robot and leg. ***Left:*** *HyQ robot on outdoor test track (2013);* ***Right:*** *first prototype of HyQ leg on vertical slider test bench (2008).*

Based on our experiences with HyQ and earlier leg prototypes (Figure 1), we have been developing a second version of the robot that improves upon the weaknesses of HyQ. It is our goal to develop a versatile machine that can be used for real-world applications. We expect that there will be situations in which the robot loses balance and falls. To allow the robot to continue with its operation, it is fundamental that it is robust to such impacts and that it can self-right after a fall. We therefore entirely redesigned the legs and the torso to increase the robot's robustness, extend its joint range of motion and increase its joint torque. This resulted in a new robot called *HyQ2Max*. Furthermore, we believe that a versatile quadruped robot used for real-world applications needs to have the option to mount a pair of dexterous arms to allow it to perform manipulation tasks. Therefore, we have been developing compact hydraulic manipulator arms that can be mounted on HyQ2Max, turning the quadruped robot into a centaur-like machine called *HyQ2Centaur*. A quadruped locomotion platform with two arms combines the stability and agility of four legs with the dexterity and functionality of a two-arm system.

This paper gives an overview of the design and hydraulic system of HyQ2Max and HyQ2Centaur. We will focus on the self-righting ability of the new quadruped robot and present the results of rigid-body dynamics simulations. To the authors' best knowledge this is the first time the design of a fully hydraulically actuated centaur robot is presented.

This paper first discusses the state of the art in the field of hydraulic quadruped machines and centaur-style robots. Section 3 then introduces the new hydraulic quadruped robot HyQ2Max, presenting the concept of its mechanical design, and the results of a simulated self-righting motion. Section 4 gives an overview of the design concept of HyQ2Centaur, focussing on the design of the new hydraulic arms. The hydraulic system of the robots is presented in Section 5. Finally, Section 6 discusses open problems and concludes the paper with final remarks.

2. RELATED WORK

This section discusses the state of the art in the field of hydraulically actuated quadruped robots and centaur-style robots.

2.1. Hydraulically actuated quadruped robots

Robotics research has resulted in a big variety of quadruped robots, most of them actuated by electric motors. A much smaller number is powered by hydraulic actuators. This section presents the most important examples.

In the 1960s, *General Electric* developed a four-legged walking truck that weighed over 1300kg. It was hydraulically actuated and controlled by a human operator. Each limb of the operator was controlling one of the robot's four legs through an interface with force feedback. After about 20 hours of training an operator was able to control the machine to walk, climb a stack of railroad ties and push a jeep out of the mud [10].

In the 1980s, Marc Raibert and colleagues constructed several hydraulically actuated legged robots, among which also a quadruped robot. The robot had four prismatic legs with 3 hydraulic joints each and a pneumatic spring at the end of the leg. It was able to trot, pace and bound on flat ground [11][12]. More recently, Raibert and his team at *Boston Dynamics* constructed several other hydraulic quadruped robots: BigDog [1], LS3, cheetah and wildcat. These robots clearly raised the bar of what is possible. However, very little information on the robot hardware, hydraulics and control has been published.

Shigeo Hirose's Titan XI is a large size hydraulically actuated quadruped robot. The 7000kg robot is designed for construction work on slopes. [13]. Statically stable walking on flat and inclined terrain has been experimentally demonstrated.

IIT's HyQ robot is an 80kg hydraulic quadruped that was first presented in 2010 in Claudio Semini's PhD thesis [14]. Since 2011 the robot is fully torque controlled and has demonstrated a wide repertoire of motions ranging from highly dynamic motions to carefully planned navigation over rough terrain. For a more detailed introduction on HyQ see Section 1.

A number of hydraulic quadruped robots have been developed in Korea and China in the last years. For example, the P2 robot [15] and Jinpoong developed by KITECH, SCalf by Shandong University [16] and BabyElephant by SJTU [17].

2.2. Centaur-style robots

While humanoid and quadruped robots are very popular among researchers in the field of robotics, a combination of the two has rarely been investigated. This section presents the state of the art in the field of centaur-style robots.

The first known centaur robot was developed by a Japanese consortium of industry and universities from 1984-1993 as part of the ART project. The project was focussing on the development of several types of nuclear inspection machines, including an electric centaur-style robot [18]. A few years later, KIST presented their centaur robot with hydraulic legs and electric upper body [19]. The robot stood 1.8 meters tall and weighed 150 kg. More recently, Tsuda et al. presented a few papers on a small centaur robot that is actuated by electric RC servomotors [20]. Several other centaur-style robots were constructed with wheels at the end of their legs (e.g. WorkPartner [21], NASA centaur 2 [22]). Even though not a full centaur, it is worth mentioning that in 2013 a video of BigDog with one manipulator arm throwing a cinder block was published online [23].

3. HyQ2Max ROBOT DESIGN

This section introduces the design concept of the HyQ2Max robot, shows the results of a study on self-righting and presents an overview of possible future application scenarios of this robot.

3.1. HyQ2Max Design Concept

The HyQ2Max robot (Figure 2) is an improved version of the hydraulic quadruped robot HyQ [2]. The main improvements are increased reliability and robustness of the robot's hardware, larger joint range of motion and higher joint output torque, as explained next.

Reliability and robustness against impacts and dirt are fundamental requirements for a legged vehicle performing real-world tasks. HyQ2Max is designed to be robust against impacts and dirt. All sensitive parts like sensors, valves, actuators and electronics are protected inside the structure. The torso is constructed with a frame made of a strong aerospace-grade aluminium alloy (7000 series), tubular roll frames in the front and back, and light-weight glass fibre/Kevlar covers that protect the onboard computer and hydraulics. The four legs are built of the same aluminium alloy as the torso. The upper leg consists of two rugged halves forming a shell that acts as protection and structural element. The lower leg is made of a light-weight yet robust aluminium tube.

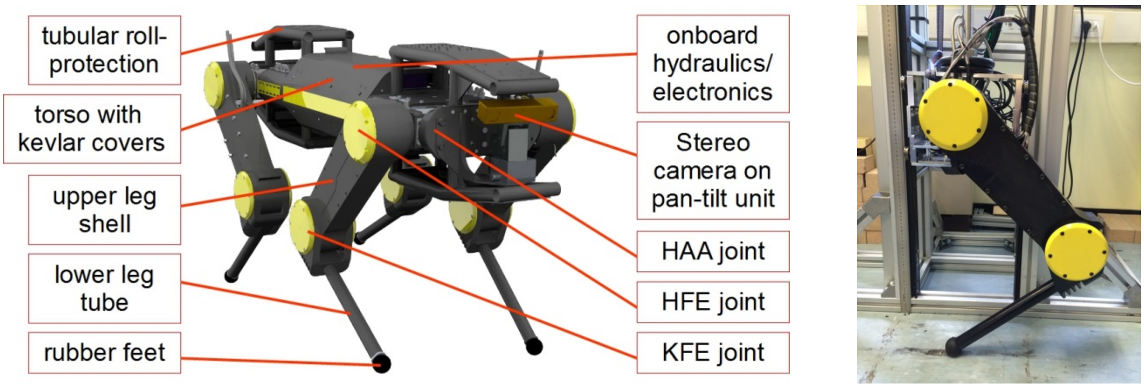

Figure 2. CAD of HyQ2Max robot and photo of single leg. ***Left:*** *CAD model of the HyQ2Max robot with explanation. The three leg joints are labelled HAA (hip abduction/adduction), HFE (hip flexion extension) and KFE (knee flexion/extension);* ***Right:*** *photo of leg prototype of HyQ2Max attached to a vertical slider test bench for experiments.*

The joints' range of motion of a legged robot determines the size of the workspace of its feet. The larger this workspace, the more versatile motions can be implemented on the robot. A large workspace is especially important for self-righting motions as explained in Section 3.2. Table 1 compares the joint range of motion of HyQ and HyQ2Max and Figure 3 confronts the two different workspaces in the leg's X-Z plane.

Table 1. Comparison of the main specifications of HyQ and HyQ2Max

Description	HyQ	HyQ2Max
Number of actuated joints	12	12
Joint range of motion (HAA, HFE, KFE)	90°, 120°, 120°	80°, 270°, 160°
Peak joint torque (HAA, HFE, KFE) @ 20MPa	120Nm, 181Nm, 181Nm	120Nm, 245Nm, 250Nm
Upper, lower leg segment lengths	0.35m, 0.35m	0.36m, 0.38m
Robot weight (offboard power supply)	80kg	80kg

It can be clearly seen, that HyQ2Max has a larger foot workspace than HyQ, leading to (1) faster running since the step length can be increased, (2) self-righting ability since the leg can be moved completely up above the robot's center of mass (see Section 3.2), (3) a rest position of the robot by retracting the legs until the bottom of the torso touches the ground and (4) an increased number of footholds for climbing motions with foothold planning.

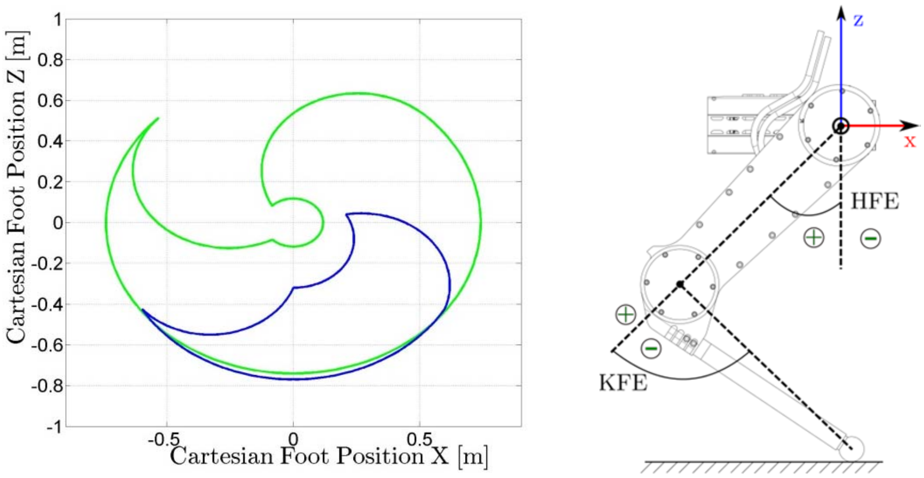

Figure 3. Comparison of the leg workspaces of HyQ (blue) and HyQ2Max (green line) in the X-Z plane (left). HyQ2Max leg drawing in the X-Z plane illustrating the angle convention and leg coordinate frame (right).

Table 1 also shows that the HFE and KFE joints of the new robot have a higher joint output torque. This is important for self-righting (see Section 3.2), carrying payload and for more agile motions. The HAA joint is actuated by a double-vane rotary actuator, the HFE joint by a single-vane rotary actuator and the KFE joint by a cylinder connected to a four-bar linkage.

3.2. Self-Righting study

As mentioned in the introduction, the self-righting capability is fundamental for a real-world legged robot, since it is unavoidable that the robot falls during its operation on challenging terrain. We therefore implemented a self-righting sequence (see Figure 4) and simulated it inside our rigid body dynamics simulator SL [24]. All kinematics and dynamics calculations are implemented with efficient C++ code, automatically generated by the robot code generator *RobCoGen* [25].

Figure 4. Self-righting sequence of HyQ2Max shown with CAD renderings: from top left to bottom right.

The joint angle and torque plots of this simulation are shown in Figure 5. The different steps of the self-righting sequence are illustrated with different colours. The thin black lines show the limits of joint angle and torques as specified in Table 1. Note that the torque limits of the KFE joint depends on the KFE joint angle since the four-bar linkage creates a nonlinear torque output profile For a detailed discussion on such output profiles, refer to [14]. The figure shows that all values stay inside their limits during the entire motion.

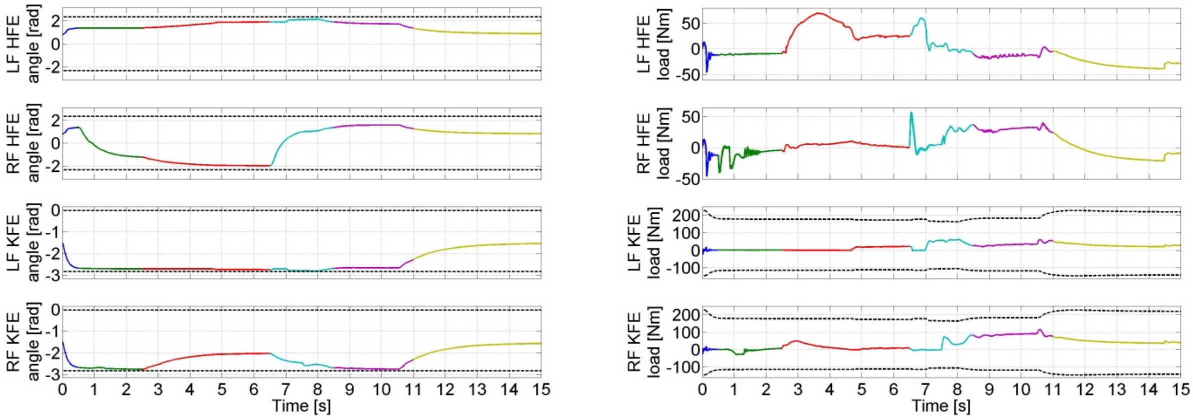

Figure 5. Simulation results of self-righting motion showing joint angles and torques for the left front (LF) and right front (RF) leg. The different colours indicate the different steps of the self-righting sequence. The black dashed line shows the joint angle and torque limits. ***Left:*** *joint angle vs. time plots of the hip flexion/extension (HFE) and knee flexion/extension (KFE) joints.* ***Right:*** *joint torques vs. time plots of the same joints.*

3.3. Possible future application concepts

HyQ2Max is designed to be the light-weight, high-performance version of this new four-legged vehicle. In the future, the robot's hardware and configuration can be customized to match the requirements of the desired application. Figure 6 shows the concept of the robot applied to a range of possible future tasks. Task-specific features range from radiation-hardened hardware (e.g. nuclear decommissioning) to specific onboard sensing (e.g. inspection) and manipulation capability (e.g. maintenance, decommissioning). The next section will discuss our current efforts to add manipulation capability to HyQ2Max.

Figure 6. HyQ2Max application scenarios. From left to right: construction, fire and rescue, forestry industry, inspection and maintenance, nuclear decommissioning.

4. HyQ2CENTAUR ROBOT DESIGN

Future quadruped robots operating in real-world applications will most likely need to manipulate objects in the environment at some point, e.g. through a pair of dexterous arms. A centaur-style robot consists of a quadruped locomotion platform and a pair of arms. It thus combines the advantages of a stable four-legged base with the dexterity of a two arm system.

This section presents the design of HyQ2Centaur, which is a combination of HyQ2Max and a pair of arms. We will first give an overview of the design of a pair of custom-built, light-weight hydraulic arms that can be mounted onto HyQ2Max. Then we will present the concept of the centaur robot design and possible future application scenarios of the centaur robot.

4.1. Hydraulic arm design

The most important requirements for a dual arms system mounted onto a quadruped robot are (1) low total weight of arms including controllers, (2) compactness, (3) torque controllability, and (4) high joint speed and torque. Commercially available solutions are either too bulky because of their heavy base and controller units (Barrett's WAM arm, KUKA's lightweight arm), not torque controlled (Universal Robots UR5) and/or too slow (HDT Robotics' MK1).

Due to this lack of commercial solutions, we have developed a compact arm with 6 hydraulic, torque controllable joints (Figure 7, left). The arm including all electronics and valves weighs around 13kg. The 6 degrees of freedom (DOF) are constructed with a combination of light-weight cylinders and rotary vane actuators. Table 2 lists the actuator type and properties of the arm's 6 joints, according to the definition shown in Figure 7 on the right.

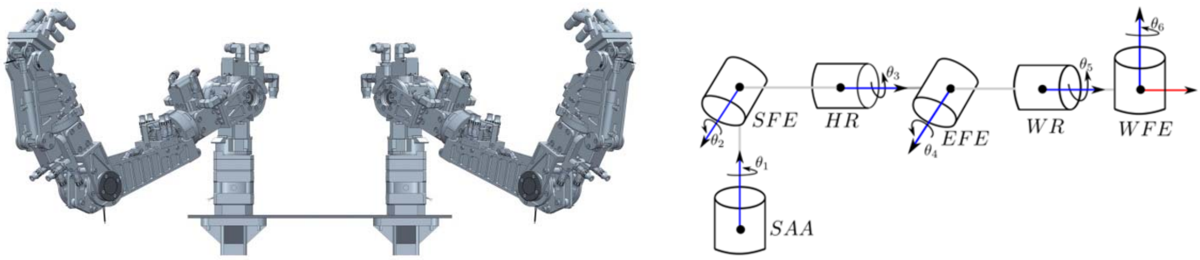

Figure 7. CAD rendering and kinematics of the new arms. ***Left:*** *CAD rendering of the new pair of hydraulic 6-DOF arms.* ***Right:*** *kinematics of the arm with the names of the joints: shoulder abduction/adduction (SAA), shoulder flexion/extension (SFE), humerus rotation (HR), elbow flexion/extension (EFE), wrist rotation (WR) and wrist flexion/extension (WFE).*

Table 2. List of the actuator type and properties of the arm's 6 hydraulic joints

Joint Name	Actuator type	Joint range	max. Joint torque/force (at 20MPa)
SAA	single vane rotary	210°	126Nm
SFE	double vane rotary	90°	120Nm
HR	double vane rotary	98°	120Nm
EFE	cylinder	130°	4kN
WR	single vane rotary	210°	60Nm
WFE	cylinder	120°	4kN

Each joint's position is measured with high resolution absolute encoders (19Bit). While the rotary actuators' torque output is measured with strain-gauge torque sensors, the cylinder force is obtained with load cells in series to the piston rod. All actuators are controlled by MOOG E024 servo valves. Distributed electronics on the arm read the sensors and create the output signal for the valve amplifiers. An EtherCAT bus connects the arm to the robot. For more detailed information on the arm design and components, see [26].

4.2. HyQ2Centaur Design Concept

HyQ2Centaur is a combination of HyQ2Max (see Section 3.1) and a pair of the new hydraulic arms (Section 4.1) as illustrated in Figure 8. The modular design of the arms allows easy mounting and removing from the robot's torso. The hydraulic interface consists of two quick release couplings for the arm's pressure and return lines. The communication interface is a single EtherCAT cable that also provides the electric power to the arm's electronic boards and valve amplifiers.

Figure 8. CAD renderings of HyQ2Centaur that consists of a HyQ2Max four-legged base and a pair of the new arms. ***Left:*** *centaur with extended arms;* ***Right****: centaur with stowed-away arms.*

The additional weight of the two arms is around 26kg. This payload is not located in an optimal position with respect to the locomotion stability. The most conservative stability criterion is static stability, where the projection of the robot's center of mass onto the ground needs to stay inside the support polygon (created by the feet in contact with the ground). Other stability criteria consider simplified dynamics of the robot to create stable locomotion (e.g. Zero Moment Point).

Since all joints of the robot can be controlled in torque [27], the robot's whole body dynamics model can be used to obtain joint torque profiles that optimise the force distribution of the four feet (and other contact points, e.g. with the arms). We have recently presented our first results with optimized joint torques that allowed the robot to climb inside a V-shaped groove [28]. The same approach allows the centaur robot in the future to optimise joint torques during manipulation tasks.

4.3. Possible Application Scenarios

Manipulation capability allows a legged robot to perform various tasks in real-world applications. Figure 9 illustrates a few of these tasks performed by HyQ2Centaur. During an inspection or rescue operation it might be necessary to open doors or to navigate over challenging terrain to open/close a valve. Other important tasks will be the remote handling of hazardous objects for example for nuclear decommissioning.

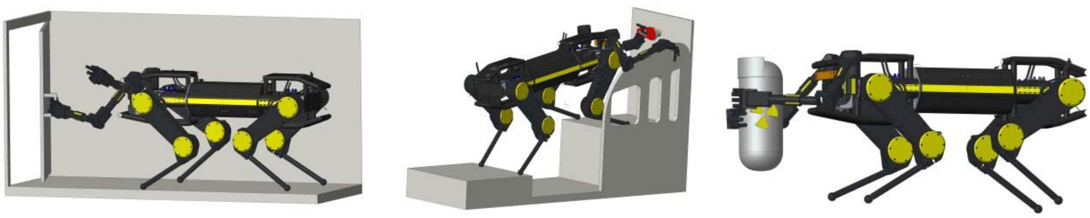

Figure 9. HyQ2Centaur task scenarios. From left to right: opening doors, full-body motion to turn valve and remote handling of hazardous materials.

5. HYDRAULIC ACTUATION SYSTEM

This section discusses the hydraulic system of HyQ2Max and HyQ2Centaur. In the current configuration hydraulic power is supplied to the robot through two highly flexible hoses. An onboard power pack is currently under development.

Figure 10 shows the schematic of HyQ2Centaur's hydraulic actuation system. For simplicity only the details of one leg are shown. The torso of the robot carries the following hydraulic system components: An accumulator to smooth out pressure ripples and provide extra flow during fast variations in hydraulic flow demand; a pressure relief valve to protect the system; a normally-open, solenoid-operated vent valve connecting the pressure supply to tank in case of an emergency and two pressure transducers. The robot's leg and arm joints are moved by cylinders and rotary vane actuators. Each joint is controlled by a servovalve.

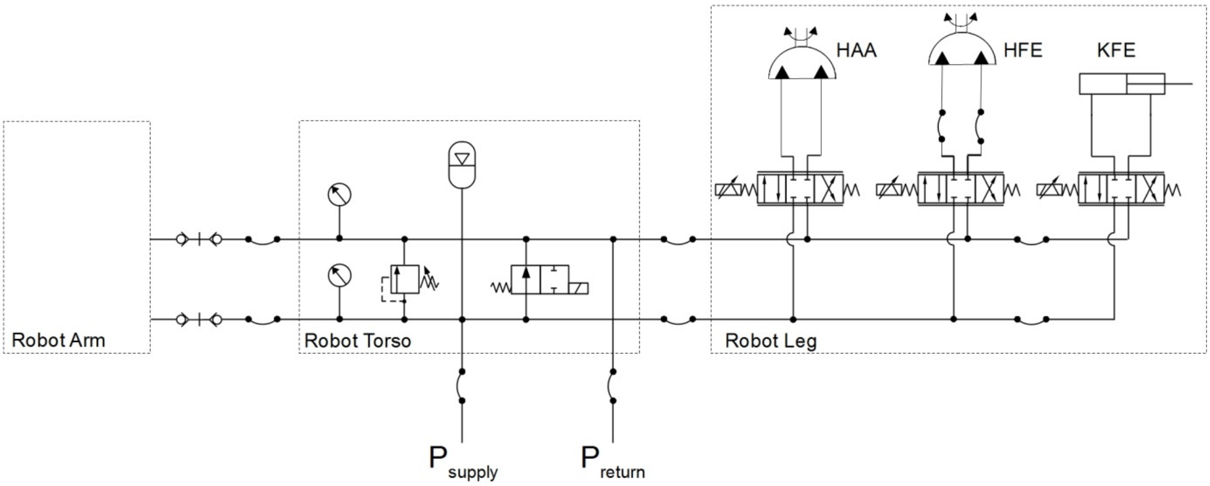

Figure 10. Schematics of the hydraulic actuation circuit of the HyQ2Centaur robot. For simplicity only the details of one leg are shown. The two arms and other legs are built up with the same actuators and valves.

6. DISCUSSION AND CONCLUSION

Open challenges in the field of hydraulic legged robots are primarily the energy efficiency of the hydraulic actuation system, the hose routing and the large size of commercially available components. Energy efficiency is especially poor in torque controlled hydraulic robots because of the internal leakage of the high-bandwidth servovalves needed for proper torque control [27]. Digital hydraulics (see [29] for a recent review) and variable pressure systems are some of the possible solutions that are currently being investigated by the research community. A neat routing of hoses across moving joints is tricky especially if the joint range of motion is large. Slip rings, custom connectors and highly flexible hoses are possible solutions. Another challenge for a hydraulic robot designer is the generally large size of commercially available components. Since the market for small scale components is (still) small, custom-made parts or expensive niche products are often the only solution.

This paper presented the design concepts of the hydraulic quadruped robot HyQ2Max and the centaur-style robot HyQ2Centaur. HyQ2Max is an evolution of IIT's hydraulic quadruped HyQ, a robot that since 2011 demonstrated various types of agile locomotion and carefully planned navigation over rough terrain. The second version has improved robustness, larger joint ranges and higher joint torques. We presented an overview of the robot's design and demonstrated the robot's self-righting ability with a rigid body dynamics simulation. Next, we showed the design of a pair of new light-weight hydraulic manipulator arms that can be mounted onto the HyQ2Max platform to turn the robot into the centaur-style machine HyQ2Centaur. Furthermore, we presented the robots' hydraulic actuation systems and discussed open research problems in the field of hydraulic legged robots. To the authors' best knowledge this is the first time the design of a fully hydraulically actuated centaur robot is presented.

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