Development of the Lightweight Hydraulic Quadruped Robot - *MiniHyQ*

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***Abstract*— This paper presents the development of the lightweight hydraulic quadruped robot *MiniHyQ*. To the authors' best knowledge, MiniHyQ is the lightest and smallest hydraulic quadruped robot that has been built so far. MiniHyQ is a fully torque controlled robot. It has reconfigurable leg configurations. It has wide joint range of motion and an onboard compact power pack. The robot has almost the same leg length as the previous robot (HyQ [1], built by our group), but its link segment lengths are $15\,\%$ less in flex configuration, due to the special isogram knee joint mechanism. Its weight is only $35\,\mathrm{kg}$ ($24\,\mathrm{kg}$ with an offboard pump unit), which makes it portable by one person. To achieve this lightweight, miniature hydraulic actuators were carefully selected, allowing us to reduce the required pump size inside the torso. By using a hydraulic rotary actuator for the hip and linear actuators with isogram mechanism for the knee joint, a wider range of motion is achieved, allowing a self-righting motion. For the design validation and hardware testing, series of experiments are conducted on MiniHyQ single leg.**

I. Introduction

Given the advances over the last few decades, legged robots are gradually becoming a promising solution for rough terrain navigation. In order to advance research faster, legged robots must become more manageable. So that dynamic experiments can be performed faster and more easily. The simplest way to achieve this goal is by reducing the size and weight of the robot. But which actuation method would be most suitable at that scale?

Traditionally, electrically actuated legged robots have suffered during highly-dynamic tasks due to the electric motors limitations. These motors tended to provide a small torque relative to their size and weight. In order to increase the torque, reduction drives were used with high ratios, in turn, reducing the maximum joint velocity. Systems such as these struggle with motion on uneven terrains due to the high, near instant, torque peaks which tend to be generated during footfall. Exceeding the maximum torque limit like this eventually results in the breakdown of the gears. To avoid these peak forces, designers normally add passive spring assemblies in series to reduce the joint stiffness. Series elastic actuation (SEA) can also be used to measure the joint torque through the displacement of the spring. By tuning the stiffness of SEAs offline they can be used effectively for running robots [2]–[4] but the inherent elasticity of SEA significantly reduces the closed loop control bandwidth [5].

Currently very few electrically actuated quadruped robots exist that are capable of performing fast and powerful motions simultaneously. The MIT Cheetah [6] is the most recent example of it which can perform tasks like running and jumping. To achieve this they used high power, low geared electromagnetic motors with proprioceptive force control.

Another common actuation method is pneumatic which allows low passive impedance but it restricts to low control bandwidth [7].

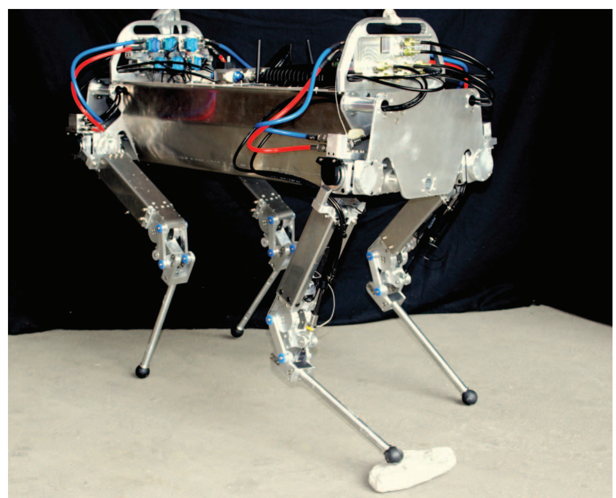

Fig. 1. Picture of the lightweight hydraulically actuated quadruped robot MiniHyQ with onboard power pack

Hydraulic actuation on the other hand is much more robust against impacts, allowing high-bandwidth control and the application of very large forces. For these reasons most mainstream dynamic legged robots like HyQ [1] and the robots from Boston Dynamics (BigDog [8], LS3, Cheetah and ATLAS) use hydraulics. However the conventional hydraulic quadrupeds are currently facing four main issues.

Firstly, the hydraulic robots tend to be bulky and it is clearly showed in a comparison made in Table I (discussed later in Section II). It makes difficult to conduct experiment with hydraulic quadruped robots. Also appropriate safety

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procedures requires a large number of people.

The second problem is that most commercial hydraulic components are focused on heavy industrial applications, for example excavators and bulldozers. Small scale hydraulics are still largely absent from the mainstream hydraulic industry and can normally only be found in niche markets.

Thirdly, hydraulically actuated robots need pump to actuate them. In the case of BigDog [8] and JINPOONG [9], they have a combustion engine to actuate the pump inside the torso. However, when using a combustion engine it is difficult to conduct indoor experiments, because of the noise and the exhaust fumes. Normally for indoor experiments an external electric pump is used to supply hydraulic power to the robot by means of two hydraulic hoses. These hoses can negatively affect the dynamics of the robots, causing unpredictable disturbances and restricting the working range of the robot in a circumference around the pump.

Lastly, existing legged hydraulic robots often lack versatility to perform a wide range of different motion. It is because of limited joint range of motion and its torque limits. From our experience with HyQ, for example during one of our recent experiments where HyQ walked over obstacles with planned footholds in a 3D map [10]: When stepping onto a pallet, stairs or over obstacles, the limited hip joint range made it difficult to impossible to retract the leg enough to avoid collisions.

The motivation for this work arose from the experience of our group (the Dynamic Legged System lab) with the quadruped robot HyQ [1]. The desire to resolve the above issues while maintaining the abilities of a world class platform led us to build a lightweight hydraulic quadruped robot.

Contributions: the main contribution of this work is the development of a lightweight hydraulic quadruped robot (MiniHyQ) with a compact onboard power pack (shown in Fig. 1). To the authors best knowledge, MiniHyQ is the lightest and smallest hydraulic quadruped robot that has been built so far. A comparison of existing hydraulic quadruped robots has been made (Table I), demonstrating how MiniHyQ lines up against the rest of the existing hydraulic quadruped robots. MiniHyQ is around 3 times lighter than most of the existing hydraulic quadruped robots. It has almost 30 % higher joint torque density (robot mass to joint torque ratio) and 40 % wider joint range of motion in leg-sagittal plane compared to HyQ. Another contribution of this work is a special knee joint mechanism (an *Isogram Mechanism*) which was added to enable a larger joint range and to allow the optimization of the joint torque curves over the whole range of the linear actuator extension. Experiments are performed on a single leg and the results are shown in Section V.

Paper Outline: the paper is structured as follows: first, in Section II we discuss related work and various existing hydraulic quadruped robots. The design of MiniHyQ is discussed in Section III. An overview of the MiniHyQ's control system is described in Section IV; next, experimental results are shown in Section V, together with a MiniHyQ self-righting task. Section VI discusses the results obtained and concludes the paper. The summary of this work is shown at the given video link in Section VII which includes the experiments preformed on MiniHyQ's single leg.

II. Related work

Since Boston Dynamics demonstrated their hydraulically actuated quadruped robot BigDog [8], the development of hydraulically actuated robots has been extensive [11], [12], [9], [13]. In Table I we show a comparison between the existing hydraulic quadruped robots. All of them are larger in size and heavier in weight. Only Jinpoong and BigDog have 4 DoF while the other robots exhibit 3 DoF per each leg. LS3 and WildCat specifications are not published yet, we can only get an idea from the online videos published by Boston Dynamics.

TABLE I

A comparison of Hydraulic Quadruped Robots

Name	**Mass** [kg] pump off (on)	**Dimensions** $[\mathrm{m}^3]$ L [m] × W [m] × H [m]	**DoF** per leg	**Trq. Ctrl.**
SCalf [12]	78 (123)	$1.10 \times 0.49 \times 1.00$	3	Yes
HyQ [1]	75 (98)	$1.00 \times 0.50 \times 1.00$	3	Yes
Baby Elephant [11]	90 (130)	$1.20 \times 0.60 \times 1.00$	3	No
BigDog [8]	N/A (110)	$1.10 \times 0.40 \times 1.00$	4	Yes
JINPOONG [9]	80 (120)	$1.10 \times 0.40 \times 1.20$	4	No
RLA-1 [13]	60.2 (N/A)	$1.10 \times 0.67 \times 1.00$	3	No
LS3	N/A	$>$ BigDog	3	N/A
Wildcat	N/A	N/A	3	N/A
MiniHyQ	24 (35)	$0.85 \times 0.35 \times 0.77$	3	Yes

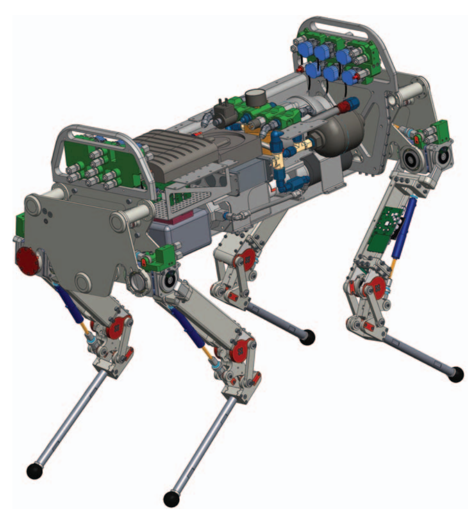

Fig. 2. The CAD model of MiniHyQ with exposed view of onboard power pack, magnetic encoder disks and EtherCat control PCB in upper leg link.

III. Design of MiniHyQ

By default, MiniHyQ is configured as forward/backward (inward-pointing) leg configuration, but it is reconfigurable as can be seen in Fig 3. Several studies [14]–[16] indicated that this configuration is suitable for quadruped robots. It reduces

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slippage between the feet and the ground which improves motion performance in general [14]. Table II shows the specification of MiniHyQ. Each leg is driven by 3 hydraulic actuators. We selected these actuators based on our scaling studies [17], [18]. In these studies we considered extreme tasks that push the actuators to their limits. This gives us a good estimation of the joint torques and velocities necessary to select the leg actuators. Each leg uses one rotary and two linear hydraulic actuators.

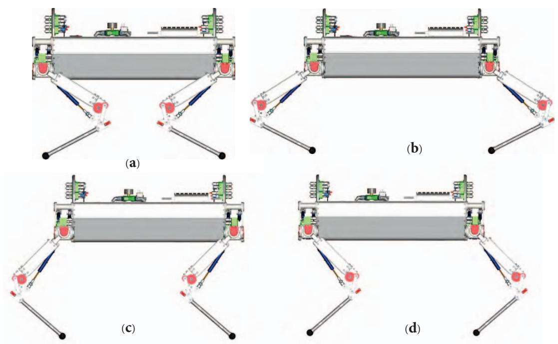

Fig. 3. Leg configurations of MiniHyQ with forward walking direction to the right: (a) forward/backward; (b) backward/forward; (c) backward/backward; (d) forward/forward.

MiniHyQ is fully torque controlled. It has an $0.85\,\mathrm{m}$ long torso which is made of $2\,\mathrm{mm}$ thick folded aluminum sheet and contains the computing system, IMU (Inertial Measurement Unit) sensor, hydraulic manifolds and compact power pack shown in Fig. II. The compact onboard power pack supplies an electric pump which provides $13\,\mathrm{L/min}$ flow rate and $20\,\mathrm{MPa}$ pressure. The MiniHyQ power pack is described in [19]. In order to keep the MiniHyQ legs as lightweight as possible, a centralized manifold is placed in the torso, rather than using distributed manifolds on each leg. High performance miniature hydraulic connectors are used to ensure that there is $0\,\%$ oil leakage. We made sure that MiniHyQ has high torque density and wide range of motion, which allows it to perform extreme tasks like self righting and high jumping, as described in Section V.

TABLE II
SPECIFICATIONS OF MINIHYQ ROBOT

Dimensions $L \times W \times H$, fully stretched legs	$0.85\,\mathrm{m} \times 0.35\,\mathrm{m} \times 0.77\,\mathrm{m}$
Weight Power Pack: offboard (onboard)	$24\,\mathrm{kg}$ ($35\,\mathrm{kg}$)
Degrees of Freedom	12 (3 per leg: 2 linear actuators, 1 rotary)
Joint Torque, Range of motion	$75\,\mathrm{N\,m}$, $90°$ HAA $60\,\mathrm{N\,m}$, $220°$ HFE $75\,\mathrm{N\,m}$, $180°$ KFE
Sensors per Leg	2 Load cells, 1 Torque sensor 3 Absolute encoders
Hydraulic Valves	12 High performance servo valves
On-board Computing	1 computer (real time Linux)
Operating Pressure	$20\,\mathrm{MPa}$
Peak Flow Rate	$13\,\mathrm{L/min}$

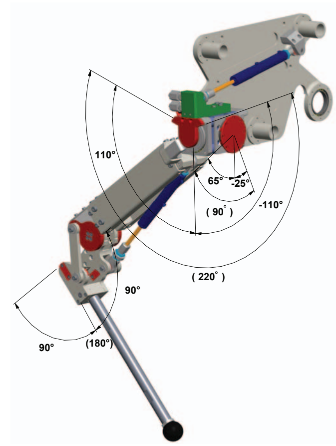

Fig. 4. CAD model of MiniHyQ Leg which consist of 3 active DoF *i.e.,* HAA, HFE and KFE.

A. Mechanical Design Of The Leg

Each leg of MiniHyQ is completely modular and it consists of 3 active joints per leg. Hip Flexion/Extension (HFE) and Knee Flexion/Extension (KFE) are the joints which work in the leg-sagittal plane. They are responsible for generating the main forward and upward motion of the robot. Most tasks like straight walking and running on flat terrain are accomplished by these joint. A rotary hydraulic actuator has wide range of motion and constant torque, although it is heavier than a linear actuator. For MiniHyQ's HFE joint we used a rotary actuator. But if we put a rotary actuator on the KFE joint, it would increase the leg inertia significantly. Thus, for the KFE joint we used a linear actuator with special knee mechanism, which not only provides a wider range of motion but also provides an optimized torque profile. The third joint, named Hip Abduction/Adduction (HAA), is less involved in the creation of forward propulsion, but it is rather responsible for the balance of the robot. Linear actuators are also used for HAA. To measure the joint torque of HAA and KFE we installed a load cell in series with the cylinder rod that measures the cylinder force that can then be mapped into a torque using the joint's Jacobian Transpose. A miniature servo valve is used to control the cylinder force and joint angle. Each MiniHyQ leg upper link is built with a folded $1.5\,\mathrm{mm}$ aluminium sheet and the rest of the leg is constructed with machined aluminum parts and ball bearings with tight tolerances to avoid backlash in the mechanism. The CAD model of MiniHyQ leg design is shown in Fig. 4.

Hip Abduction/Adduction (HAA)

The HAA is an important joint for a quadruped robot because it support its weight and it needs to react quickly to keep its balance. It requires a reasonable joint torque and velocity. We use an asymmetric hydraulic cylinder, which has a bore diameter of $13\,\mathrm{mm}$ and a rod diameter of $6\,\mathrm{mm}$ with $68\,\mathrm{mm}$ stroke length. It weighs $0.11\,\mathrm{kg}$, one end of it is connected on top of Hip Flexion/Extension (HFE) joint rotary actuator, while the other is connected to the torso plate shown in Fig. 5.

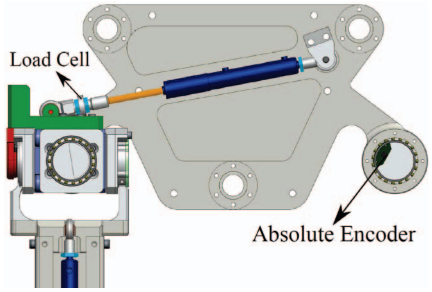

Fig. 5. CAD model of the HAA joint: the cylinder is connected on top of rotary actuator.

To measure the joint torque we installed a load cell in series with the cylinder rod that measures the cylinder force that can then be mapped into a torque. The torque profiles are shown in Fig. 6 for cylinder extension and retraction.

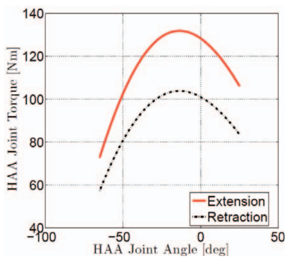

Fig. 6. Torque profile of HAA joint for cylinder extension (red solid line) and retraction (black dashed line)

Hip Flexion/Extension (HFE)

MiniHyQ's HFE joint is based on a hydraulic rotary actuator. It has a joint range of motion of $220°(-110°$ to $110°)$ and it provides a constant joint torque of $60\,\mathrm{N\,m}$ at $20\,\mathrm{MPa}$. A high resolution absolute encoder is used for position sensing, shown in Fig. 7 (left), and a strain gauge based custom designed torque sensor is displayed in Fig. 7 (right).

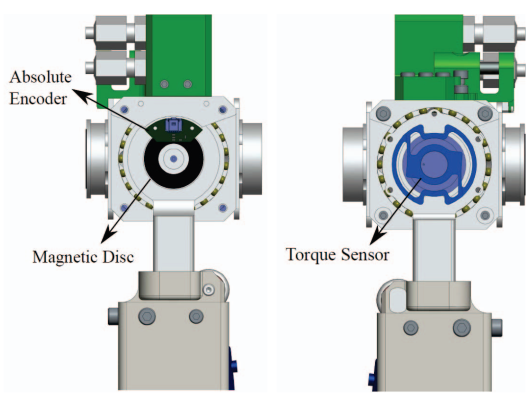

Fig. 7. CAD model of HFE. *Left:* mounting of absolute magnetic encoder and magnetic disk. *Right:* the other side of the motor, with custom designed strain gauges-based torque sensor inserted into the HFE motor spline shaft.

Knee Flexion/Extension (KFE)

We proposed an isogram mechanism for KFE joint [20], which is based on the crossed four-bar linkage [21]. It has a changeable instantaneous center of rotation (CICR) like a human knee joint. We optimized a set of design parameters to obtain a smoothly distributed torque profile that provides high torque in a retracted joint configuration (*i.e.,* flexed leg) and high velocity (but lower torque) when approaching the fully extended configuration. The joint range of motion is $180°$.

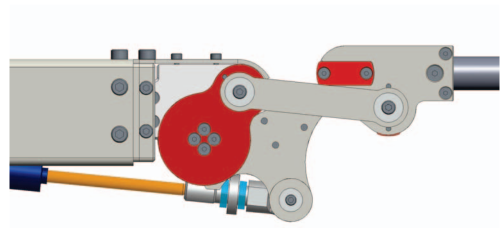

Fig. 8. The CAD model of MiniHyQ KFE joint

The isogram mechanism based knee joint mainly consists of two links: a *triangular* and a *cover* link which connect the upper and lower leg segments as shown in Fig. 9. The triangular link is directly connected to the linear actuator at node 5 which creates a rotation of node 5 about node 1 resulting in a knee joint rotation about the CICR with the help of a cover link. Its other two nodes 1 and 3 are connected with the upper and lower leg segments, respectively. The cover link connects both upper and lower links through node 2 and 4. The black dot in Fig. 9 marked with *ICR* represents the instantaneous center of rotation (ICR), which is the intersection point of the cover and triangular link. Due to a changing center of rotation (polycentric rotation or CICR) of the proposed knee joint, the definition of the joint angle with respect to cylinder extension has to be derived as explained next.

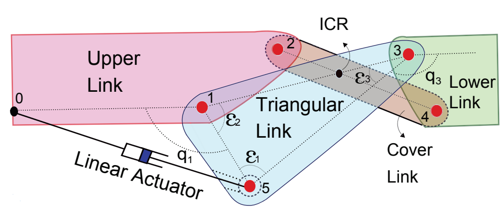

Fig. 9. Schematic representation of the isogram mechanism based MiniHyQ's knee joint.

The knee joint angle q is defined as the angle between the long axis of the upper link and the long axis of the lower link. It can be expressed as the sum of the angle q_1 and q_3 as follows:

$$q = 180° - (q_1 + q_3 - \varepsilon_1) \quad (1)$$

where ε_1 is fixed angle of triangular link shown in Fig. 9. Equation (1) results in a knee angle equal to zero when the leg is fully extended (straight) and $180°$ when it is fully retracted.

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MiniHyQ has changeable instantaneous virtual upper and lower link lengths due to the CICR. The link lenghts get almost $15\,\%$ shorter when the leg is fully retracted, as can be seen in Fig. 10 (right). As shown in one of our most recent works [18], the quadruped with the shorter link lengths in a squat position requires less desired torque for performing a squat jump. Figure 10 (left) shows the knee joint angle q with change in cylinder extension x_{cyl}.

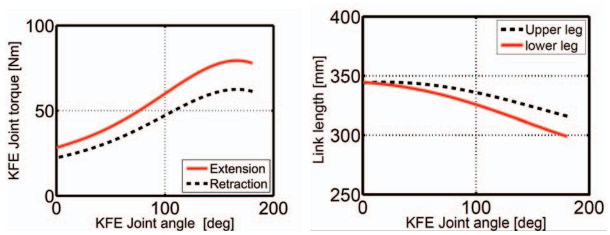

Fig. 10. *Left:* isogram knee joint torque profile with respect to knee angle. *Right:* the instantaneous virtual upper and lower link lengths with respect to knee angle.

Due to the CICR, it is not possible to install position sensors that directly measure the joint angle. Therefore, we installed absolute (high-resolution) encoder at node 1 (see Fig. 9) to measure q_1 that can then be mapped into a joint angle q.

IV. MiniHyQ Control System

The control system architecture of MiniHyQ is shown in Fig. 11. It basically consists of a main unit and 4 leg units. In the main unit, control PC running Linux kernel patched with real-time Xenomai takes care of all low level control of servo valves via main I/O board and high level control such as leg trajectory. Leg unit collects input signal from 3 magnetic encoders, 2 force sensors ($\pm 4448\,\mathrm{N}$) and 1 custom designed torque sensor, and sends these data to the main unit. For the communication between each unit, we use an EtherCAT bus, which guarantees high speed and real time communication.

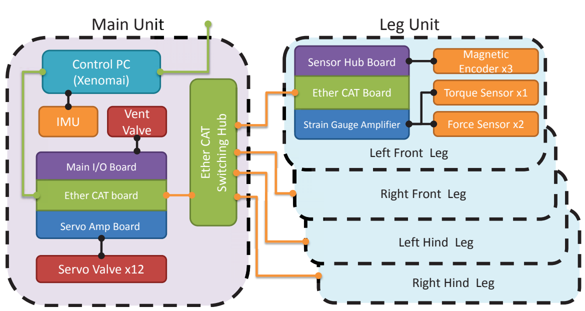

Fig. 11. MiniHyQ's control system architecture

For simulation and real-time control software, SL (Simulation Laboratory) developed by Stefan Schaal [22] is used. Since SL can be used for both simulation and real robot controller, we can conduct experiments and simulations seamlessly.

As a low level controller, each joint is fully torque controlled based on HyQs torque controller [23]. Full torque control allows the robot to perform active compliance which is essential to cope with impacts during dynamic motions. Furthermore inverse dynamics can be used for improving control of locomotion [24].

V. Experimental Results

MiniHyQ's self-righting sequence is shown in Fig. 14. For the design validation, the initial experiments are performed on MiniHyQ's single leg connected to a slider which allows leg only move in vertical direction. Experimental setup can be seen in Fig. 13. For initial testing of the leg, we attached the $3\,\mathrm{kg}$ load to its foot and swing it in the air at $1.2\,\mathrm{Hz}$. Figure 12 shows its result, with reasonable torque tracking and poor position tracking. These preliminary results are taken by using very simple low level hydraulic controller without taking into account velocity and pressure compensation terms [23]. Further experiments are demonstrated at the given video link in Section VII.

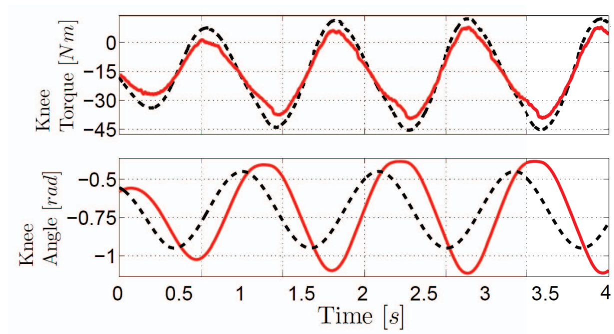

Fig. 12. Plot of experimental measured data (red solid), reference data (black dashed) for the leg swinging the air at $1.2\,\mathrm{Hz}$ with $3\,\mathrm{kg}$ load attached to foot. *Top:* knee joint torque. *Bottom:* knee joint angle.

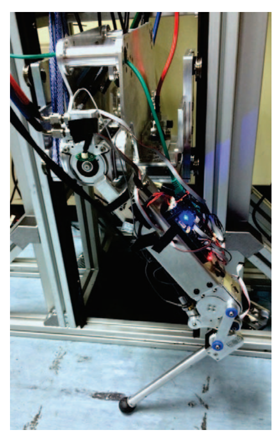

Fig. 13. Experimental setup. Single MiniHyQ leg is connected to a slider slider which allows it to move freely up and down (vertically). For the initial leg testing, the electronics hub board is attached at outside of upper link.

VI. Discussion & Conclusion

MiniHyQ is a pioneer, slightly smaller in size than the previous robot HyQ [1] but MiniHyQ is the lightest among

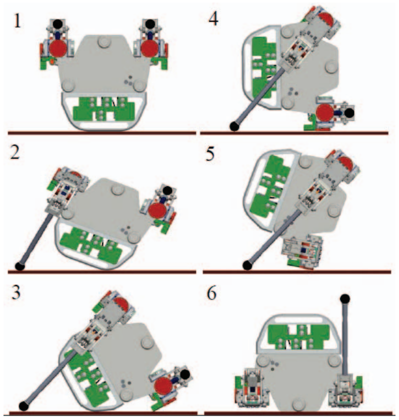

Fig. 14. Self-righting sequence, front view. From 1 to the 6: After a fall the robot lies on its top. To right itself, the robot first has to move the feet of the two legs at one side and push to the ground up to turn its torso. The HAA will then rotate to push the robot up until the CoG passes the pivot point of the frame. As a consequence, the robot will then roll back onto the bottom of the torso. The retracted legs will then extend to move the robot back onto its feet.

all the existing hydraulically actuated quadruped robots. The development of this robot is a significant step forward in miniature hydraulics in robotics. We demonstrated the development of lightweight hydraulic actuated quadruped. We also show novel knee joint: despite its higher complexity, the isogram mechanism is superior to the traditional design, because its many kinematic parameters can be fine-tuned to achieve an optimal torque profile. Such profiles should preferably lead to a robotic leg that is strong in a flexed configuration and fast when almost extended. For the design validation and hardware testing, series of experiments are conducted on a MiniHyQ leg. It includes a demonstration of its range of motion, joint velocities at different speeds, leg swing in air with load attached to foot and push up action when leg is under load.

Future work: Future experiments will be performed on MiniHyQ using the onboard power pack. The versatility of robot will be demonstrated in future work by performing different motion and gaits using its wide range of joint angles.

VII. Appendix – Video contents

At the given video link, the summary of this work is shown which includes experiments preformed on MiniHyQ single leg.

`http://youtu.be/Yux0FMzUzPo`

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