Design of a Hydraulically Actuated Arm for a Quadruped Robot

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A common disadvantage of quadruped robots is that they are often limited to load carrying or observation tasks, due to their lack of manipulation capability. To remove this limitation, arms can be added to the body of the robot, enabling manipulation and providing assistance to the robot during body stabilization. However, a suitable arm for a quadruped platform requires specific features which might not *all* be available in off-the-shelf manipulators (e.g. speed, torque-controlled, light-weight, compact, without external control unit). In this paper, we present a systematic approach to design a robotic arm tailored for an 80kg quadruped robot. A full robot with arms and legs (aiming for a *centaur*-style robot) was simulated performing a range of "representative" tasks to estimate joint torques and velocities. This data was then extensively used to select the design parameters, such as the joint actuators to develop a novel, compact (0.743m fully extended), light-weight (12.5kg), and fast (maximum 4m/s no-load speed at end-effector) hydraulically actuated robotic arm with 6 torque-controlled degrees of freedom. The enclosed video presents preliminary experimental results.

Keywords: Manipulator Design, Hydraulically Actuation, Torque Controlled, Hydraulic Quadruped, Multi-legged Robot

1. Introduction

How does a robot transverse highly uneven terrain? And what does it do when it gets to its destination? This is an area that is expected to be covered by legged robots. On the whole, quadrupeds have the advantage (over bipeds) of improved stability, whilst not becoming overly complex (like hexapods). Traditionally quadrupeds have been limited to load carrying or observation tasks, as they have no manipulation ability. This paper presents a "best-of-both-worlds" approach, by a bespoke arm system which can be mounted on the hydraulic quadruped robot HyQ,[1] in a single or bimanual configuration, creating a centaur robot. In its normal standing posture, the body of HyQ is around 1m from the ground, weighs roughly 80kg and features 12 torque-controlled joints powered by hydraulic actuators. The arm system will add a new dexterous manipulation capability to the already wide range of abilities of the HyQ such as trotting, running, jumping, stabilization, external disturbance rejection,[2] quick reflex action,[3] and careful foot hold planning during navigation through unstructured terrain.[4] This enables new tasks to be performed, including: removal of obstacles, grasping and manipulating objects, opening doors, or robot balance assistance (Fig. 1). Today, a huge variety of robotic arms are commercially available. Most

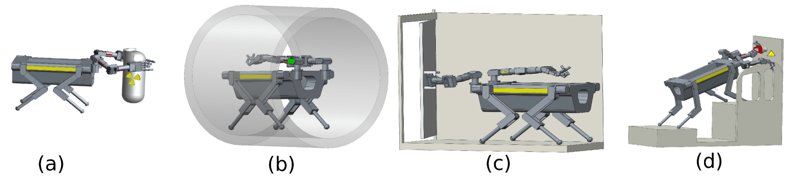

Figure 1. Conceptual tasks for the centaur robot (a) Carrying an object (b) Passing through a narrow passage (c) Opening a door (d) Body stabilization of the robot

of them suffer from limitations: some are very heavy and only allow position control (e.g the hydraulically actuated arms: $Hydra-MP$ by KNR and $ATLAS-7R$, $CONAN-7P$ by Schilling Robotics). Others, are torque controlled but need a bulky external control unit ($LWR3$ by DLR[5]), are limited in joint-speed ($MK1$ by HDT[6]) or have low payload lifting capacity (Schunk's $LWA3$) or, like WAM sold by Barrett Technology,[7,8] have a heavy base ($27kg$). The limitations, of these existing manipulators reduce the number of potential application scenarios and the possibility to be integrated onto an agile mobile robot such as HyQ.

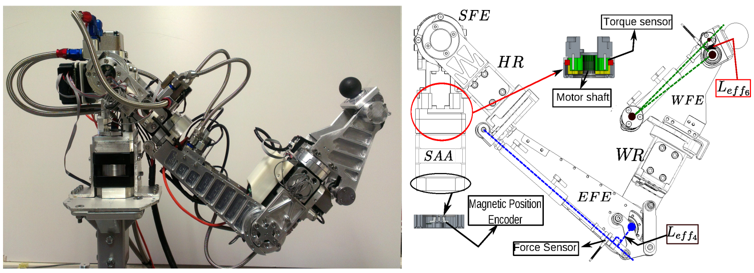

Figure 2. The HyArm: (left) Real robot side view (right) CAD model showing actuator arrangement (see section 4 for further details)

The main contribution of this work, is the design of a novel **Hy**draulically actuated **Arm** (HyArm) which addresses all the abovementioned limitations present in off-the-shelf manipulators (see Fig. 2) (e.g. fast, torque-controlled, light-weight, compact, without external control unit). In this paper, we present a systematic approach to design a robotic arm tailored for an 80kg quadruped robot. We developed a simulation of a centaur robot to acquire design parameters for the arm, such as joint torque and speed by simulating a range of dynamic "representative" tasks on the centaur robot. The arm can also be easily mirrored to provide a dual arm system (see section 5). Throughout this document, we will mainly focus on the design of the arm with only a short discussion regarding the control. The paper is structured as follows: Section 2 describes the design specifications, Section 3 presents simulations of "representative" tasks. The mechanical design of *HyArm* is presented in Section 4. Finally Section 5 draws the conclusions and presents future works directions. Section 6, provide youtube link of simulation and real robot experiments (under torque controlled)

2. Design Specification

The first crucial step in the design process of the arm is to define the specifications that make the arm suitable for our desired applications (e.g. perform fast manipulations, lift objects, and help the robot to balance).

The rationale followed in the design is to be compact, without any external control unit, modular, light-weight, and being able to move a heavy payload. We chose to have the joints *hydraulically actuated* and *torque-controlled*. Indeed hydraulic actuators are well known for their robustness when coping with high force peaks during impacts. This feature becomes essential when performing highly dynamic motions whilst interacting with the environment. On the same line, is preferable to have a torque controlled actuator, because due to the physical nature of the impacts, they are better dealt within the torque domain.[9] Therefore, implementing torque control is a priority for our design. Another advantage of using hydraulics is that the HyQ already has an hydraulic supply. The arm will be equipped with position and force/torque sensors at each joint, in order to implement impedance/torque control schemes.[9] We choose to have six DoF in the arm, which is the minimum requirement to define position/orientation in 3D space. From a purely kinematic point of view, the arm is designed as a chain of revolute joints. Inspired by human arm anatomy, each actuated joint is labelled as follows: Shoulder Adduction/Abduction (SAA), Shoulder Flexion/Extension (SFE), Humerus Rotation (HR), Elbow Flexion/Extension (EFE), Wrist Rotation (WR) and Wrist Flexion/Extension

(WFE) as shown in Fig. 3.

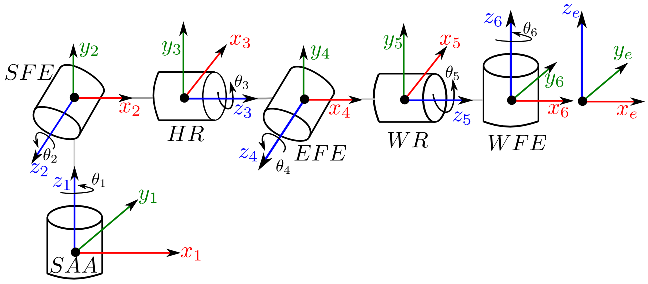

Figure 3. HyArm kinematics: Shoulder Adduction/Abduction (SAA), Shoulder Flexion/Extension (SFE), Humerus Rotation (HR), Elbow Flexion/Extension (EFE), Wrist Rotation (WR), Wrist Flexion/Extension (WFE) All the joints are shown at zero configuration

3. Simulation

This section presents the simulation results for a set of "representative" tasks allowing the estimation of torque and velocity profiles for actuator selection (see subsection. 3.1). The robot model used in the simulations is a floating base quadruped robot with two arms (see Fig. 4 of Centaur). We used SL[10] that is a real-time simulation environment for rigid bodies, where we implemented the controller as well. To build the dynamics for the simulated robot, we used $RobCoGen$,[11] a model based code generator to provide kinematics and dynamics of articulated robots.[12] Given the kinematic tree of the robot and its inertia properties, RobCoGen automatically generates forward/inverse dynamics and kinematic transforms targeting different software platforms. The parameter for the HyQ robot are taken from the CAD model. To calculate inertia properties for the robotic arm simulation (considering the design specifications given in section 2), we selected each link as represented by an aluminum cylindrical link of mass $2kg$, length $0.175[m]$, diameter $0.075[m]$ with material density of $2700[kg/m^3]$.

3.1. *Representative tasks*

We designed the "representative" task trajectories to be demanding in terms of torque or velocity, for a single or a combination of joints. We developed minimum jerk trajectories for the end-effector of the arm in the Cartesian space (unless otherwise specified). These then resulted in the motion of the arm joints. The remaining joints are kept in a default configuration. An impedance control law defined both for position and orientation

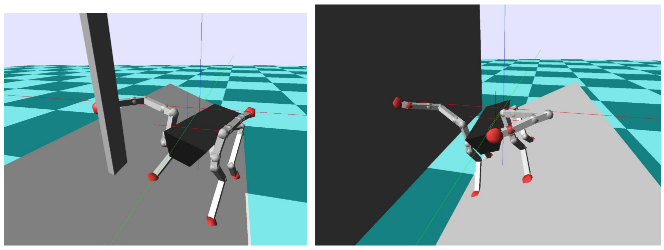

Figure 4. Picture of the Centaur simulation during the pull-up (left) and push-up (right) tasks.

sets the virtual forces/torques (F,T) at the end-effector. We also simulated the robot falling to estimate fall time. Fig. 5 summarizes required torque and velocity plots for each joint for all simulated tasks. The explanation of each simulated task is presented as follows:

(a) **Lifting an object**: This task simulates the centaur robot lifting an object located at the end-effector when the arm is fully extended. It demands high torque for shoulder and elbow joints. We set three different kind of trajectories for shoulder joints: *horizontal* (SAA), *vertical* (SFE), *humerus rotation*. Each scenario has been simulated *with* and *without* payload which are two different estimations for maximum joint *torque* and *velocity*, respectively. We set a conservative payload of $5kg$ at end-effector moving at speed of about $1.5m/s$ for the shoulder joints. These trajectories were also simulated without payload at a speed of $4m/s$ (three times faster than the robot falling time).

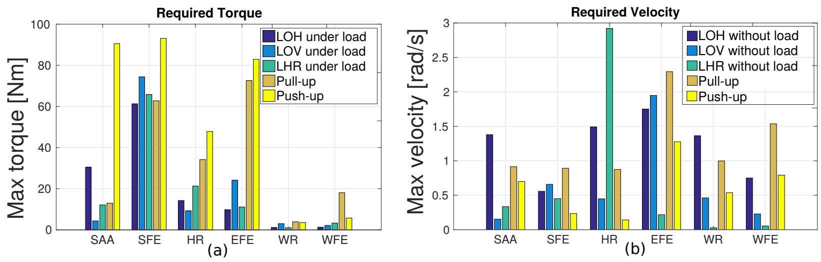

Figure 5. (a)Required torque and (b) velocity for lifting an object, biceps curl, pull-up and wall push-up tasks for each arm joint. LO:**L**ifting an **O**bject, V:**V**ertical, H:**H**orizontal, HR:**H**umerus **R**otation

(b) **Pull up**: This task demands a high torque output for the shoulder and elbow joints. In this task an arm is holding a vertical beam and pulling the robot torso (up to $0.3m$) towards the beam while standing on a slope of 0.5 *rad* inclination (Fig. 4 (left)). This task resembles opening a door or pulling an object.

(c) **Wall push-up**: The wall push-up task (Fig. 4(right)) demands high torque for shoulder and elbow joints. For this task the robot is standing on a 0.5 *rad* inclined slope and performing a push-up motion against a wall which resembles to provide assistance to robot while climbing stairs or to balance.

4. HyArm Design

The simulated tasks of Section 3, provided the required peak torques, and velocities for each DoF. According to simulated data, we intended to select commercially available hydraulic actuators which are as light weight and compact as possible.

The HyArm joints are actuated with a combination of rotary and linear hydraulic actuators Fig. 2. The benefit of using this combination is to achieve large joint ranges while still ensuring both a compact and lightweight design. The HyArm shoulder joints ($3DoF$) are equipped with rotary motors to improve compactness (also keeping the shoulder CoM closer to the base, which reduces the arm inertia) with a constant torque output. The elbow joint is actuated by a hydraulic cylinder. A four bar linkage (inspired by the excavator bucket joint) has been designed for this joint to achieve a good trade-off between joint range-of-motion and output torque. This choice has the advantage that the whole elbow assembly is part of the upper arm. The wrist joints play an important rule in determining end-effector position and orientation. For the WR joint we selected a rotary actuator to achieve wider range-of-motion, while the WFE joint is actuated by a cylinder. A standard lever mechanism provides the required range-of-motion and torque for the WFE joint.

Referring to Fig. 2(right) (elbow and wrist assembly) using known geometric calculations (law of cosines) we developed the kinematic relationship between the angles θ_i and the effective lever arm L_{eff_i}. The effective lever arm is the quantity which allows to map joint angular velocity $\dot{\theta}_i$ and torque τ_i into cylinder linear velocity $\dot{x}_{cyl_i} = L_{eff_i}(\theta_i)\dot{\theta}_i$ and force $F_{cyl_i} = L^{-1}_{eff_i}(\theta_i)\tau_i$, where $i = 4, 6$ represents the joint numbers (EFE and WFE respectively). The HyArm is equipped with position encoder, torque and force sensors (see Fig. 2(right)) to achieve torque control. Table. 1 presents an overview of the arm specification. The enclosed video (see section 6) presents preliminary experimental results. The HyArm is demonstrating torque controlled capability to change joint impedance and user and robot interaction while performing a continuous motion with different speeds.

Table 1. System Overview of HyArm Robot

Specification	Value	Joint	Total range-of-motion	Torque/force
Arm extension	0.743m	SAA	-3.14/0.52 [rad]	126[Nm]
Weight	12.5kg	SFE	-0.74/0.83 [rad]	120[Nm]
Maximum payload	10kg	HR	-1.57/0.068 [rad]	120[Nm]
Actuation system	Hydraulics	EFE	0/2.21 [rad]	225[Nm_{peak}]
Degree of freedom	6Dof (3+1+2)	WR	-2.01/1.57 [rad]	60[Nm]
Control mode	Position/torque	WFE	-1.57/0.52 [rad]	100[Nm_{peak}]

5. Conclusion and Future work

We presented the design process of a compact and light-weight hydraulic robotic arm that is fully torque controlled, compact, light-weight and without an external control unit (Table. 1). Hence, perfectly suitable to be mounted on quadruped robots which are meant to perform sophisticated dynamic tasks. The design evolution of the HyArm is presented step-by-step starting from task simulations to estimate the joint torques and velocities necessary to select the actuators and for the mechanical development. Each joint is equipped with position encoder and torque/force sensors to be torque controlled with powerful hydraulic actuators.

Future works will mainly focus on robustness testing, implementation of more robust controllers, and experimental studies of dynamic tasks and flow estimation for hydraulic supply with the quadruped robot (see Fig. 6).

Hardware changes will deal with improving hydraulic hose routing, weight reduction and the design of a light-weight hydraulic gripper. An intensive study will be performed to find a suitable attachment position for one or dual arm system with the HyQ robot. This will involve walking simulation of the robot with arm(s) while performing manipulation task and testing with real robot.

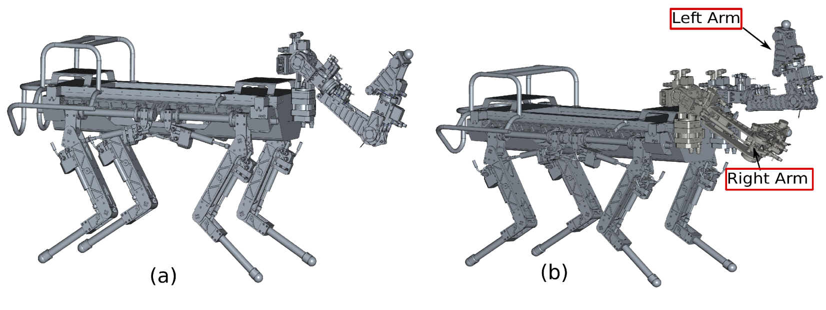

Figure 6. Future work: (a) The HyQ robot with the HyArm (b) The HyQ with dual arm system (Centaur robot)

6. Appendix

The youtube link of simulation and real robot experiments (under torque controlled): `http://youtu.be/JhbHPZc-NGU`

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