Centaur Robots - a Survey

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Recent developments in the field of multi-legged mobile manipulators encouraged researcher to develop new robotic platforms combining the locomotion stability of multi-legged robots with manipulation capabilities. This paper provides an extensive bibliography that can be of help to researchers interested in further studying and designing centaur-like robots. A centaur is a mythological creature with the upper body of a human and lower body of a horse. Similar to the centaur, half-human and half-horse composition in robotics can be exploited to achieve stability and manipulation capabilities.

Keywords: Centaur-like Robot, Multi-legged Mobile Manipulator, Quadruped Robot

1. Introduction

Today, mobile robots are able to access a wide range of terrain types with different levels of difficulty. Wheeled and tracked robots have great maneuvrability in an environment where the terrain is smooth, flat, and with well-structured surfaces (e.g, roads, indoor environment). In recent years, there has been a number of successful deployments of wheeled and tracked robots in off-road environments (e.g, Curiosity Rover developed by NASA JPL and 710 Kobra by iRobot). However, the majority of these robots still have limitations and difficulties to navigate in unstructured and rough terrain. The goal to overcome these limitations in wheeled or tracks robots, along with studying the capabilities of legged animals, led researchers to develop biologically inspired legged robots. The trunk of the legged robot is decoupled from uneven ground by articulated legs. It allows the trunk to be independent of the roughness of the terrain, since the legs provide active suspension within their kinematic limitation. During a step cycle, a leg first leaves the contact with the ground (lift-off) to then enter the swing phase. Before the touch-down at the end of the swing phase, the legged robot can decide where to put the foot next. The ability to select these footholds within its kinematic reach allows a legged robot to traverse highly uneven terrains. To this end, quadruped robots have the advantage (over bipeds) of improved balance, while not becoming overly complex (like hexapods). Traditionally quadrupeds have been limited to load carrying or observation tasks, as they have no manipulation ability. One approach is to combine *best-of-both-worlds* by a bespoke arm system mounted on a quadruped robot to create a *centaur-like* robot. A centaur is a mythological creature with the upper body of a human and lower body of a horse. Similar to the centaur, half-human and half-horse composition in robotics can be exploited to achieve stability and manipulation capabilities.

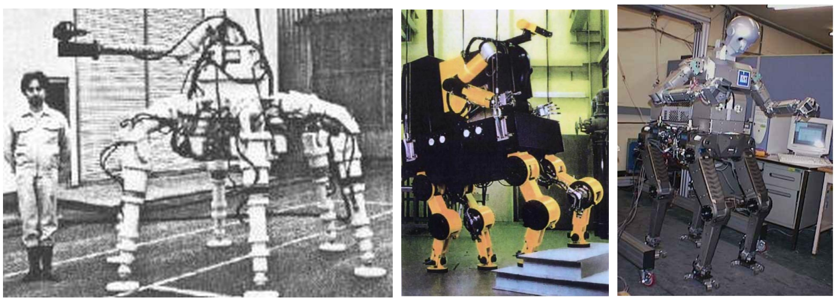
This paper contributes as a survey of centaur-like robots. The centaur-like robot belongs to the class of *multi-legged mobile manipulator robots*. Today there exists a vast variety of mobile manipulators. They can be categorized based on their: (a) locomotion system that allows motion by legs only, or as combination of legs and wheels (hybrid), or by wheels only, (b) their actuation system; and (c) target mobility environment such as ground, underwater or space. This survey on mobile manipulators focuses primarily on quadruped robots with single or dual manipulator(s). It also includes hybrid mobile manipulators which use legs and wheels for locomotion.

2. Overview of Centaur-Style Robots

This section provides an overview of the state of the art of centaur-style robots.

2.1. *AQUAROBOT*

The first known multi-legged mobile manipulator was AQUAROBOT. It was developed by a Japanese consortium of industry and universities starting from 1984 to 1993 as part of the Advanced Robotics Technology research association (ART) project. The project was focus on development of robots for nuclear plants, undersea oil rigs and disaster prevention in refineries. The first field test of AQUAROBOT for underwater inspection was done in 1990.[1] The AQUAROBOT has six legs to walk underwater at $50m$ depth. Each leg had $3DoF$ and they were electrically actuated by DC-motors. It was equipped with a TV camera and ultrasonic ranging device at the end of a manipulator mounted on the mobile platform as shown in Fig. 1a.



(a) AQUAROBOT (b) HITACHI-ART Centaur (c) KIST-Centaur

Figure 1. Images of (a) AQUAROBOT, (b) HITACHI-ART Centaur and (c) KIST-Centaur (see Appendix A for image sources)

2.2. *HITACHI-ART Centaur*

The first centaur-like robot was developed by HITACHI and ART as part of a same project mentioned above. They developed an electric centaur-like robot as shown in Fig. 1b.[2] This robot was developed to perform nuclear plants inspection and maintenance. There is no published work about robot design or specifications or tasks capabilities. It had four legs, two arms with hands, upper human-like torso and an on-board camera system.

2.3. *KIST-Centaur*

A few years after the ART project, a similar robot was developed by the Humanoid Robot Research Center and KIST Korea called *Centaur*,[3] as shown in Fig. 1c. This robot stood $1.8m$ tall and weighed $150kg$. The KIST-Centaur had overall 37 DoF. It had four $3DoF$ hydraulically actuated legs. The upper body was electrically actuated by DC servo motors with reduction gear trains including harmonic drives. The upper body looked like half a human with $25DoF$. It had a $2DoF$ torso, a neck with $2DoF$, two $7DoF$ of arms with two $3DoF$ hands and $1DoF$ mouth. It had an on board Li-Ion battery with 20 minutes of operation time. The KIST-Centaur was equipped with force sensors at each wrist and head with stereo vision camera. An on-board microphone enabled the robot to perform voice recognition. All the servo control, wireless communication and power supply was embedded inside the robot body. The robot was controlled either in teleoperation or autonomous mode. For teleoperation, an exoskeleton of master arms was designed to control the dual arm system.

2.4. *Tsuda-Centaur*

Tsuda et al. developed a centaur-like robot based on a humanoid robot.[4] They used two robots, one as front body, legs and arm; and the other one for lower body (legs) as a back of the centaur body attached with plastic plates as shown in Fig. 2a. The Tsuda-Centaur overall consists of $34DoF$. It has four legs with $6DoF$, two arms with $4DoF$, $1DoF$ in its waist and $1DoF$ for its head. All joints were actuated by electric RC servo motors. Tsuda et al. developed a software architecture and controller based on humanoid robots. They showed that upper and lower body motions can be controlled separately. They carried out experiments to evaluate their centaur-like robot motion capabilities. They showed that their robot can walk smoothly by moving diagonal legs (similar to trotting). They tried different human-like motion developed for their humanoid robots. They concluded that human-like motion cannot directly be applied to centaur-like robots.[5]

2.5. *BigDog and SpotMini*

Recently, Boston Dynamics attached a custom built hydraulically actuated manipulator to BigDog, creating a multi-legged mobile manipulator. The designed manipulator consists of overall $8DoF$ including gripper as shown in Fig. 2b. The morphology and scale is similar to a human arm. It has $3DoF$ in shoulder, $1DoF$ in elbow and $3DoF$ for wrist.[6] The manipulator is mounted in front of BigDog. It allows a workspace in front, laterally, below and above the robot. There is no published data available for manipulator weight, joint range-of-motion or torque. But, BigDog with the arm demonstrated throwing of a $16.5kg$ cinder block in one of their youtube video. Boston Dynamics also developed a new electrically actuated, light and compact multi-legged mobile manipulator named SpotMini, as shown in Fig. 2c. Beside the impressive capabilities in terms of locomotion and manipulation there is no technical specification provided, a youtube video is showing SpotMini performing various manipulation tasks with robust locomotion capabilities. The goal of their work is to enable BigDog interact with objects in man-made environments. They have shown that using robot whole-body control including the legs and arm results in improved strength, velocity and workspace for the manipulator. For the cinder block throwing task[6] off-line planned trajectories were applied to the arm controller while the robot was trotting. The off-line trajectory generator plans the foot location and body forces while satisfying physical constraints. (Specifically,

(a) Tsuda-Centaur (b) BigDog (c) SpotMini

Figure 2. Images of (a) Tsuda-Centaur, (b) BigDog and (c) SpotMini (see Appendix A for image sources)

the center of pressure location, joint torques, speed and kinematic limits). The result is similar to a human athlete that maximizes distance in the discus event by performing a precise sequence of choreographed steps.

2.6. *WorkPartner*

WorkPartner is the prototype of a service robot to work with humans in outdoor environment.[7] The mobile platform is based on a hybrid system. It combines legs and wheels to locomote over uneven terrain (Fig. 3a). It

(a) The WorkPartner robot (b) Robonaut2-Centaur2 by NASA

Figure 3. Images of (a) The WorkPartner robot and (b) Robonaut2-Centaur2 by NASA (see Appendix A for image sources)

has four legs equipped with wheels. Each leg has $3DoF$ joints and an active wheel. The upper body consists of a $2DoF$ torso, two $3DoF$ arms and a camera & distance measuring laser pointer head with $2DoF$. The upper body is mounted onto the front of the robot mobile base which makes it look like a centaur. It is electrically actuated and has an on-board power system, a hybrid with batteries and $3KW$ combustion engine. it weighs about $250kg$, including all mechanical components, actuation, power and computing systems. The target applications and work tasks for WorkPartner: garden work, cutting down of the forest, picking trashes, transferring of lightweight obstacles, environment mapping.

2.7. *Robonaut2-Centaur2*

Robonaut2 is an extension of the earlier designed robot Robonaut1[8] by NASA. Later NASA and General Motors teamed up to develop Robonaut2.[9] Robonaut2, uses brushless DC motors, harmonic drive gear reductions, and electromagnetic fail-safe brakes and series elastic actuators as the building blocks. It has two torque controlled $7DoF$ robotic arms with $9kg$ payload lifting capacity at full extension and two hands with $12DoF$. Each arm joint actuator is integrated with custom planar torsion spring and 9 bit absolute angular position sensors to measure spring deflection. All arm joints and wrist are equipped with force/torque sensors. All the electronics are integrated into the upper arm. The Robonaut2 has a $3DoF$ head equipped with cameras. The upper body is made of aluminum with steel and weighs $150kg$. The total height from the waist to head is 1m and the shoulder width is 0.8m. The Robonaut2 torso is attached to a rover with four legs and wheels as feet, called Centaur-2 as shown in Fig. 3b. The target applications and work tasks for this robot is to provide assistance to astronauts in space and perform exploration tasks.

2.8. *Momaro*

Momaro is an electrically actuated robot developed by the Autonomous Intelligent Systems Group at the Computer Science Institute of University of Bonn, Germany (see Fig. 4a). It has four legs with steerable wheels as feet. The wheels allow omnidirectional driving and the legs adjust the height of the upper body. It has two $7DoF$ arms and two grippers. Each gripper has four individually controllable fingers with two joints each. Its upper body can rotate with respect to its base.

It is equipped with an on-board vision system and battery. Strictly speaking, Momaro is not a multi-legged robot, but a hybrid of legs and wheels mobile manipulator. During the DARPA Robotics Challenge (DRC) in 2015, Momaro performed mobile manipulation tasks, but never used its legs for legged locomotion, like walking. It showed that using legs to change

(a) Momaro (b) Aero (c) Grit

Figure 4. Images of (a) Momaro, (b) Aero and (c) Grit (see Appendix A for image sources)

robot height results in enhanced workspace. In 2015, the University of Bonn teamed up with European universities and companies including IIT to start a European project called CENTAURO[a] to build a centaur-like robot for search and rescue missions.

2.9. *Aero*

Another centaur-like robot that participated in the DRC is called Aero, build by RT engineers from Japan (see Fig. 4b).[10] It consists of a total of $38DoF$. It has two arms with $7DoF$, 2 hands with $2DoF$, four $4DoF$ legs with wheels as feet and a torso with $3DoF$. Aero has an on-board vision system mounted onto a neck with $3DoF$. It is electrically actuated powered by SEED solution actuators. Its total weight is $50kg$ and height is about $1.6m$. During the DRC, it just used its wheels to traversed some of the rough terrain, but was not able to finished the task.

2.10. *Grit*

Grit also participated in the DRC. It was developed by a small self-funded team of students, professors and professional engineers (see Fig. 4c). It has four legs with wheels as feet, two arms and a torso that makes it resemble a centaur-like robot. It weighs $27kg$ and its height is about $1.2m$. Grit is an

[a]https://www.centauro-project.eu

electrically actuated robot. There is no published information about joint range-of-motion, speed, torque, and degrees of freedom.

2.11. *LAURON-V*

LAURON-V is a hexapod robot designed by FZI Research Center for Information Technology, Germany. It has six electrically actuated legs with $4DoF$ in each leg. The LAURON-V robot was designed to participate in search and rescue missions. It weighs $42kg$ which includes on-board battery, computers, sensors and electronics and has $10kg$ payload capacity.[11] It can stand on the four hind legs by shifting its CoM location inside the support polygon, leaving the two front legs to use for single or dual manipulation tasks as shown in Fig. 5a. Each front leg can carry a payload of less then $1kg$. The robot has shown static manipulation without moving while holding an object. Recently, it has been upgraded with retractable gripper which allows to manipulate different objects with a single leg.

(a) LAURON-V (b) TITAN-IX

Figure 5. Images of (a) LAURON V and (b) TITAN-IX (see Appendix A for image sources)

2.12. *TITAN-IX*

Hirose et al.[12] developed a quadruped called TITAN-IX for demining missions. Each leg has 3 degrees of freedom with specialized mechanisms for their feet. The foot mechanism[13] allows each leg to change their end-effector tool e.g. gripper, sensor, or mower. TITAN-IX, has demonstrated three tasks at a time such as walking, exchanging the end-effector tool and manipulation as shown in Fig. 5b. The manipulation task is done remotely using a master gripper, which teleoperates the slave gripper on the quadruped side. They have exhibited tool attachment/detachment, grasping and digging on single static leg teleoperated by a master gripper.

(a) RoboSimian (b) Interact Centaur

Figure 6. Images of (a) RoboSimian and (b) Interact Centaur (see Appendix A for image sources)

2.13. *RoboSimian*

RoboSimian was develop by Jet Propulsion Laboratory JPL to participate in the DRC as shown in Fig. 6a.[14] The goal of the RoboSimian development is to operate in a degraded human environment and perform tasks normally executed by a human. RoboSimian is one of its kind, it uses four limbs and hands to perform both mobility and manipulation. It has two active wheels on its body and two passive caster wheels on its limb to achieve passively stable posture. It has four identical limbs and each joint uses identical electric actuator. The actuator design consists of a DC brushless motor connected to a 160:1 harmonic drive, cross-roller bearings and magnetic safety brake. It has two position sensors (a) an optical incremental encoder on the motor rotor and (b) a capacitive absolute position sensor on the actuator output. All the electronics, including safety, communication and microcontroller are integrated within the actuator units. Each limb has $7DoF$ which is divided into 3 identical sub-assemblies, the so-called elbow assembly and azimuth assembly actuator is connected to the body. An elbow assembly consists of two actuators integrated orthogonally with the connecting structure. Repairing and field support during testing are easier as only a single actuator unit needs to be swapped out. The end of each limb is equipped with a 6-axis force/torque sensor to detect the interaction with the environment and to serve as an interface to the end-effector.

2.14. *Interact-Centaur*

The Interact robot, also called *Interact-Centaur* (Fig. 6b) is developed by ESA's Telerobotics & Haptics Laboratory collaboration with the TU Delft Robotics Institute. The robot consists of a four-wheeled mobile platform. To interact with the environment or manipulate objects, two $7DoF$ robotic LWR III arms with grippers are mounted in front of the robot. To provide visual information, the robot has an on-board camera system equipped with a $6DoF$ pan-title unit and laser scanners.

2.15. *HyQ - multi-legged mobile manipulator*

In 2015, IIT's HyQ robot[15] was equipped with the new hydraulic manipulator *HyArm*[16] to create a multi-legged mobile manipulator.[17] This robot is fully torque-controlled and has 18 hydraulically-actuated DoFs. A picture of HyQ with the HyArm is shown in Fig. 7. The hydraulic and electric power is supplied from HyQ to HyArm. The arm electronics are connected to HyQ's on-board real-time control PC through an EtherCat network. The weight of the mounted arm is $12.5kg$. This additional weight in front of the robot can negatively affect the robot's balance since the CoM of the quadruped is shifted to the front. Rehman et al.[17] proposed a new control framework to address this problem by optimizing the Ground Reaction Forces (GRFs) of the quadruped and coping with external/internal disturbances created by the manipulator.

3. Conclusions

This paper presented an overview of the centaur-style robots that were built and published to date. Centaur-style robots have a promising morphological structure due to the combination of the stability and mobility of a quadruped base with the manipulation capabilities of a single or dual arm manipulator system.

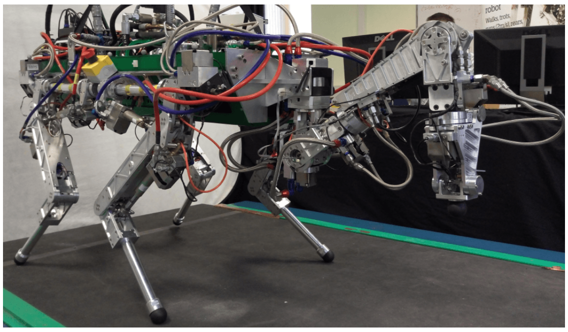


Figure 7. Picture of IIT's HyQ robot[15] with the new hydraulic manipulator HyArm[16] attached to its front creating a multi-legged mobile manipulator.

Appendix A. Image Sources

Image	Source
Fig. 1a	http://cyberneticzoo.com/early-underwater-manipulators-and-robots/
Fig. 1b	http://www.plasticpals.com/?p=32515
Fig. 1c	http://isrlab.tistory.com/29
Fig. 2a	Cited paper of Tsuda et al.[4]
Fig. 2b	https://www.youtube.com/user/BostonDynamics
Fig. 2c	https://www.youtube.com/user/BostonDynamics
Fig. 3a	Cited paper of Ylonen et al.[7]
Fig. 3b	https://commons.wikimedia.org/wiki/Category:Robonaut_2
Fig. 4a	http://archive.darpa.mil/roboticschallenge/finalist/nimbro-rescue.html
Fig. 4b	http://archive.darpa.mil/roboticschallenge/finalist/aero.html
Fig. 4c	https://www.gritrobotics.co/cog-burn/
Fig. 5a	Cited paper of Hirose et al.[11]
Fig. 5b	Cited paper of Hirose et al.[12]
Fig. 6a	http://archive.darpa.mil/roboticschallenge/finalist/robosimian.html
Fig. 6b	http://www.esa.int/spaceinimages/Images/2015/09/The_Interact_Centaur_Rover
Fig. 7	Cited paper of Rehman et al.[17]

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