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PETMAN: A Humanoid Robot for Testing Chemical Protective Clothing

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1. Introduction

Petman is an anthropomorphic robot designed to test chemical protective clothing (**Fig. 1**). Petman will test Individual Protective Equipment (IPE) in an environmentally controlled test chamber, where it will be exposed to chemical agents as it walks and does basic calisthenics. Chemical sensors embedded in the skin of the robot will measure if, when and where chemical agents are detected within the suit. The robot will perform its tests in a chamber under controlled temperature and wind conditions. A treadmill and turntable integrated into the wind tunnel chamber allow for sustained walking experiments that can be oriented relative to the wind. Petman's skin is temperature controlled and even sweats in order to simulate physiologic conditions within the suit. When the robot is performing tests, a loose fitting Intelligent Safety Harness (ISH) will be present to support or catch and restart the robot should it lose balance or suffer a mechanical failure. The integrated system: the robot, chamber, treadmill/turntable, ISH and electrical, mechanical and software systems for testing IPE is called the Individual Protective Ensemble Mannequin System (**Fig. 2**) and is being built by a team of organizations.†

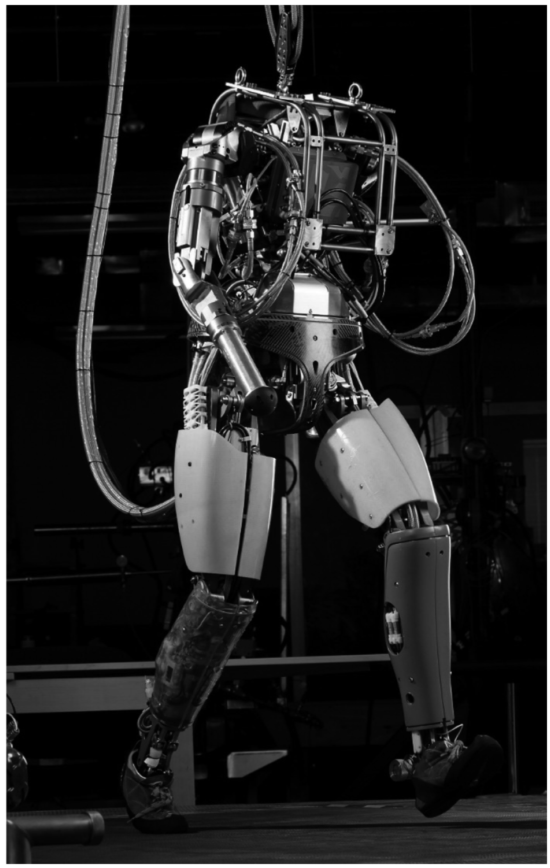

Fig. 1 The Petman robot walking on a treadmill

In 2009 when we began the design of Petman, there was no humanoid robot in the world that could meet the requirements set out for this program. Previous suit testing robots such as Portonman from the Defense Science and Technology Laboratory used external actuation or fixtures to support the robot during exercises. Limitations of these systems include a limited repertoire of behaviors or the compromise of the protective suit where the external fixture attaches to the robot. Other humanoid robots from the research community have demonstrated impressive movement without external support. Perhaps Petman's nearest neighbors are the Humanoid Robot Project's HRP series of robots [1] and the hydraulically powered Sarcos Primus humanoid [2]. The key challenges in creating Petman were to build a robot, with human anthropometry, that could simultaneously achieve human-like strength, speed and motion

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Fig. 2 The Individual Protective Ensemble Mannequin System will be used to test chemical protective clothing. It is comprised of the PETMAN robot, the Intelligent Safety Harness, a containment chamber and wind tunnel, treadmill and turntable, and a control station for preparing and monitoring tests

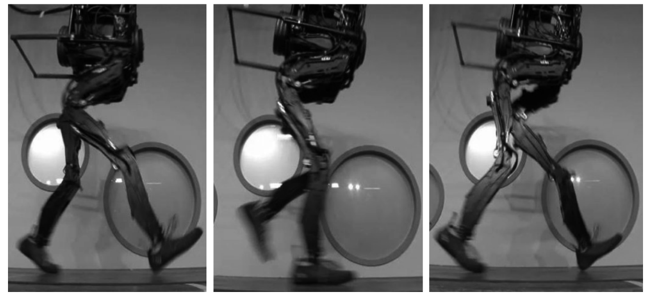

Fig. 3 PETProto walks with a natural heel-to-toe gait. PETProto was built quickly using BigDog hardware in order to accelerate control development

while wearing human clothing, including footwear.

PETMAN achieves compact, high strength actuation using hydraulics. An innovative and tightly integrated mechanical design achieves large range of motion at the joints while keeping all mechanical and electrical systems within the envelope of an average male soldier[†]. A flexible tether that enters the robot at the ankle supplies hydraulic and electrical power, cooled water, and communications with the robot. To date PETMAN has demonstrated dynamically balanced, heel-to-toe walking at a range of speeds up to 4.8 [km/h] (3 [mph]). Using motion scripting software we have created, the robot has demonstrated 2 hour endurance tests in which it performs programmed sequences of motions including stand, squat, squat while turning, side-step with arms raised overhead, and walk.

The goal of this program was to design and deliver PETMAN in just 3 short years. A key challenge facing us was to develop control software that would allow a bipedal robot to dynamically balance with a natural, human-like gait. In order to make progress on this while PETMAN was being designed and built, we quickly developed a simple biped, called the PETMAN Prototype, early in the program.

2. The PETProto Robot

The PETMAN Prototype biped (PETProto) was built from existing BigDog [3] hardware. Using BigDog legs and electronics allowed us to build this robot in four months. PETProto has two, five degree-of-freedom (DoF) legs: the upper-most DoF being abduction/adduction at the hip, the remaining DoFs nominally moving the leg parallel to the sagittal plane (**Fig. 3**). PETProto is about 1.5 meters tall, with the hips about 1 meter above the ground. The hips have a 19 [cm] lateral separation, which is similar to that of a human.

With PETProto, we were able to demonstrate a dynamic, heel-to-toe, bipedal walking gait. The robot, starting from a stand, was able to walk at varying speeds as high as 7.2 [km/h] (4.5 [mph]). By design, the control of the robot's cadence and step length, as a function of walking speed, mimicked that of a human of similar size. Additionally, the approximately 44 [kg] robot was able to carry a payload of 40 [kg]. While walking, it could regain its balance when pushed moderately from the side, though disturbances that caused large crossover steps between the legs were challenging. PETProto was also able to walk, without control modifications, with varying human footwear (from slender climbing shoes — size 10 US, with a maximum width of 9.5 [cm] — to large army boots), and with a hydraulic tether attached to one leg just above the ankle (to simulate how PETMAN itself would eventually be tethered to hydraulic power). We will discuss more about PETProto and PETMAN in the Controls section below.

3. Design of PETMAN

PETMAN is a free standing biped robot powered by an off-board hydraulic power unit via a tether that enters the right ankle. It weighs about 80 [kg] with an additional payload capacity of 23 [kg], is 140 cen-

[†]Fig. 1 shows PETMAN in a laboratory test configuration prior to upper body skin integration.

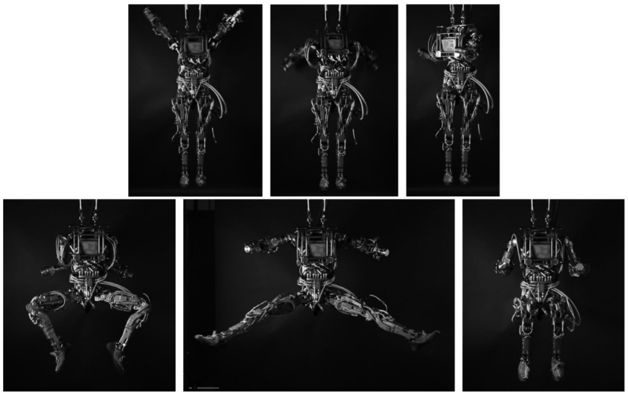

Fig. 4 PETMAN uses hydraulic actuation to produce the large range of motion and high strength required for natural human-like behavior

Fig. 5 PETMAN's skin was developed by Measurement Technology Northwest. The rigid skins control temperature and sweat rates of the robot. Flexible joint sleeves provide an airtight seal without impeding the normal range of motion of the robot

timeters tall at the shoulder, and has an outside body form that closely conforms to a 50th percentile male body form. Onboard systems include actuation, sensing, computation and controls. Twenty nine joints, with integrated sensors for measuring position and force, are actuated with either low-friction hydraulic cylinders, or compact hydraulic rotary actuators. Hydraulic flow to the actuators is regulated by aerospace-quality servovalves. The robot has the following actuated joints [joint:#DoF]: ankle:2, knee:1, hip:3, back:3, shoulder:3, elbow:1, wrist:2, neck:2. One passive DoF in each wrist and foot provide compliant interaction with the environment.

The hardware design process used to create PETMAN started with defining a set of human motions including jumping jacks, walking, sitting, transitions from standing to prone, crawling and others that are typical of soldier tasks. Motion capture data collected from subjects performing these behaviors provided kinematic information used to define required joint ranges of motion (RoM). Dynamic simulations were then used to evaluate joint torques which in combination with RoM data provided the basis for the PETMAN actuator design requirements. We implemented a spiral development process in which preliminary mechanical designs were incorporated into dynamic simulations of the robot which were in turn used to refine actuator requirements and thus mechanical design. This process resulted in a 29 DoF robot capable of the strength and large RoMs required for realistic, dynamic human motions.

The robot skin (**Fig. 5**) is comprised of hard shells that incorporate thermal regulation and perspiration. Shells are connected by flexible joint-sleeves. The shells and sleeves create an airtight seal that nominally prevents any chemicals from passing through the skin of the robot. Nevertheless, the robot is designed to tolerate chemical intrusion and decontamination if necessary.

An onboard computer reads the sensors, performs both low and high level controls functions, and handles communications with a remote human operator. Onboard communication uses a modified CANBus protocol to support a 1 [kHz] control loop. The onboard computer also records large amounts of engineering data for performance and failure analysis, and operational support.

PETMAN has about 90 sensors. Inertial sensors measure the attitude and acceleration of the body, while joint sensors measure the motion and force of the actuators. The onboard computer integrates information from these sensors to provide estimates of how PETMAN is moving in space. Other off-board sensors in the hydraulic power unit monitor PETMAN's homeostasis: hydraulic pressure, flow and temperature.

4. Intelligent Safety Harness

A three-cable harness system called the Intelligent Safety Harness (ISH) is used in conjunction with an overhead electric power hoist to ensure safe, automated handling of the robotic mannequin system. The purpose of the power hoist is to raise and lower the robot between experiments. During experiments the hoist cable is slack. In contrast to the power hoist, which bears the full weight of the robot, the ISH uses lower forces and finer control.

The ISH uses 2.45 [mm] steel cables to connect a rigid overhead structure to a loose fitting harness worn exterior to the robot's IPE. Each of the three cables has two electric motors which allow high-bandwidth force control and the ability to spool out cable regardless of cable tension.

The ISH serves two main functions: to assist robot behavior if necessary and sense robot position. The ISH assist functionality is used if a loss of balance is detected or if external force is temporarily required during extreme motions. The robot position sensing functionality allows the robot control system to locate the robot on the treadmill.

In practice, the ISH was not used during development of the PETMAN walking behaviors. Rather than use the ISH "to cheat", we found that it was easier to develop a walking gait without it. Once the walking gait was working, the robot could tolerate the disturbances provided by the ISH without additional changes to the control software. Alternatively, some of the more delicately balanced motions, such as the side-step with hands overhead, required some assistance from the ISH to reliably maintain robot stability.

5. Controls

5.1 Walking

PETProto and PETMAN walk using a hybrid hierarchical control architecture. This hybrid control consists of discrete and continuous components. The discrete component is primarily responsible for control of balance using foot placement, and thus has a dominant influence on the robot's forward and lateral motion. The continuous component is responsible for control of body height and orientation, and can also influence balance by modifying the forces exerted by the stance leg, including actively moving the center-of-pressure (CoP) of the feet.

Legs that are in swing are handled by the discrete part of the hybrid control, which consists of two core pieces: a step-by-step balance controller and a hierarchical swing controller. The balance controller uses foot placement to control the forward and lateral motion of the robot, and builds on the balance control used by BigDog. The essence of our implementation is to monitor the location of the instantaneous capture point [4] using intelligent estimation of body state. The controller then calculates where to place the swing foot relative to the capture point in order to balance the robot as well as achieve desired body motion. This placement location also considers the mechanics of how the foot will interact with the ground, which can differ sagittally and laterally. The desired body motion includes nominal desired forward and lateral velocities, as well as a lateral body oscillation that will achieve proper foot separation. The hierarchical swing controller is responsible for planning a trajectory for the swing leg, relative to the body, that will place the swing foot at the desired touchdown location specified by the balance controller. Local position controllers on the swing leg joints then follow desired joint motion specified by inverse kinematics, taking into account practical constraints such as joint limits and avoiding collisions with the stance leg.

Legs that are in stance are controlled by the continuous part of the hybrid control. This is a hierarchical structure that starts with high-level posture control of the body. The posture control is responsible for regulating the height and orientation of the body. It is also responsible for following desired upper body trajectories, such as desired pelvis, back, and arm motion. The posture control uses a virtual servo on the body to generate virtual forces that correct deviations from the desired body posture and motion. A force distribution algorithm then decides how to best realize these virtual forces using the stance leg, given the available support footprint. Finally, low-level force control on the stance leg, with redundancy management, generates the desired foot forces specified by the higher-level algorithms.

Using these controllers, PETMAN is able to walk at speeds up to 4.8 [km/h] (3 [mph]). The control architecture allows for goal data (from motion capture of human walking) to influence the motion of the robot, especially with the upper body or where kinematic redundancy is present. Using such goal data during walking, PETMAN can mimic human upper-body motion in the back, shoulders, and arms. This upper-body motion also plays an important control role in counter-acting inertial reactions due to leg swing accelerations. This makes the overall, whole-body motion during the gait look more natural. Also, like PETProto, PETMAN is able to walk with different types of footwear and with the hydraulic tether attached just above the right ankle.

5.2 Other Behaviors

Petman is also able to perform a set of additional suit-stressing motions, such as squatting from a stand, a check-six (twisting the pelvis, torso and head to look behind oneself while in a squatted position), a slow speed jumping jack (a side-step with arms raised overhead), and moving from a stand to kneeling on one knee. For balance, these motions use a kino-dynamic planning algorithm that is similar to ZMP motion planning [5]. The algorithm is given desired starting and ending poses for the robot and a set of geometric constraints on where the CoP can be as a function of time. It then finds a body trajectory (and CoP trajectory) that satisfy the CoP limits and boundary conditions of starting and ending poses. Low-level position control at the joints, driven using a redundancy-handling and singularity-robust inverse kinematics algorithm, drives the robot through the desired poses. Replanning is done between certain sub-phases of the motion, with feedback from the sensed kinematics allowed to influence the evolving motion.

6. Test Preparation and Monitoring Software

IPE tests will be planned and monitored from a control station that allows users to prepare, review, and execute a test. A test script is constructed using a drag-and-drop interface, allowing the operator to sequence robot motions, changes to skin temperature and perspiration, and turntable headings. Beyond these built-in test script primitives, operators may include custom robot motions they design themselves using a motion editing program. A simulator allows the user to review the test sequence prior to executing the test.

During test execution, the software system monitors skin sensors, sequences robot motions, coordinates between and monitors all robot-related subsystems, and displays relevant robot, chamber, and skin chemical sensor information to the user. 3D graphical displays of robot state as well as video of the live performance are shown alongside plots of robot data. Separate software components on different computers control things such as robot motion, ISH motion, treadmill speed, robot skin, and the hydraulic power system. A central software component, the IPEMS Control System (IPEMCS) acts to manage these various subsystems. The IPEMCS monitors subsystem status, coordinates subsystem execution to run the test script, and forwards status information to control room interfaces. It records relevant skin sensor data and robot motion data for post-test analysis of IPE performance, and caches high-rate subsystem data for diagnosis of any hardware problems.

7. Future work

Boston Dynamics has begun the development of a new humanoid robot. The Atlas robot, whose development is funded by the Defense Advanced Research Projects Agency (DARPA), will build upon the software and mechanical advances of Petman to advance the state-of-the-art in rough terrain mobility. The focus of this effort will be on creating new software and hardware that enables Atlas to coordinate the use of its hands and feet to maneuver in tightly congested spaces or difficult and steep terrain. Such a humanoid robot could potentially be used to respond to disasters such as the damaged Fukushima nuclear power plant. The goal is to build a robot that can maneuver through rubbled terrain that is currently impassable by contemporary robots and then maneuver upright using its free hands to open doors, use tools, and operate equipment.

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