GuRoo: Autonomous Humanoid Platform for Walking Gait Research

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Abstract: This paper describes the design and construction of an autonomous humanoid call the GuRoo. The robot has been built as a research platform for experiments in robust biped walking gait generation for humanoid robots. The proportions of GuRoo are based on anthropomorphic data, and match closely to human form and mobility in all major respects. The robot is completely autonomous, with on-board computing provided by a central handheld computer networked to DSP based digital control boards using a CAN bus. Power is supplied by on-board batteries with sufficient energy to power walking gait for one half hour of typical operation. The platform has been tested with a number of simple movements including waving, shaking hands, crouching, standing on one leg, and open loop walking.

1 Introduction

The world we live in has been built by humans with the aim to aid humans. Ergonomics now influencing the design of just about all man made objects and spaces, from kettles, stairs and chairs to offices, kitchens and sports stadiums. For robots to integrate seamlessly and become a ubiquitous part of human life, it is essential that this current human environment be unmodified. As a result of this, it is argued that robots must take a humanoid form to interact easily within the environment that humans have built. Humanoid robotics is a growing field of robotics research with numerous major projects around the globe. Several major Humanoid projects include Honda's Asimo [1], University of Waseda's WABIAN [2] and the University of Tokyo's H7 [3]. Each of these projects has constructed a humanoid robot for use in their respective walking research departments.

1.1 The GuRoo Project

The GuRoo project seeks to solve the challenge of building a humanoid robot that can compete in a game of soccer against both human controlled and autonomous opposition. To meet this challenge, there are a multitude of different problems that need to be solved. The robot must be able to move freely and stably and must be able to deal with an unstructured, dynamic environment as well as physical contact and disturbances. It must be able to sense its surroundings; the ball, other players, the field and the goal. It must also be completely autonomous, receiving no support, physical or computational, from humans.

These problems are yet to be solved, with further research into balance, coordination and perception planned over the coming years. At this stage, the project has developed an excellent platform for further research.

1.2 Paper Overview

Section 1 outlines the motivation and aims for the GuRoo humanoid project. Section 2 describes the mechanical construction and choice of actuators as well as the morphology of the robot. The electrical architecture of the distributed control system is outlined in Section 3. Section 4 describes the major components of the software design required to run the robot, from the hight level gait generation to the firmware located on each board is presented. Section 5 and 6 present several experiments performed on the platform and the results respectively.

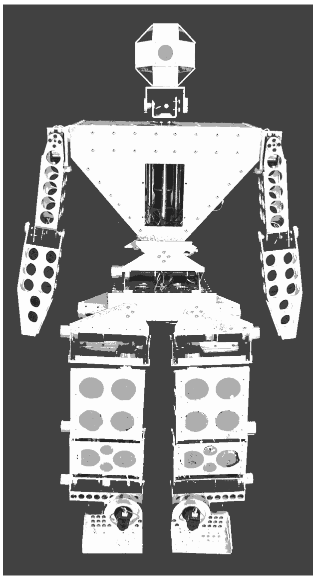

Figure 1: The GuRoo Humanoid Robot Platform

2 Electro-Mechanical Platform

The GuRoo is an anthropomorphic robot, with proportions modelled on statistical data from a United States Survey [4]. It is designed to be completely autonomous, with space and mounting points for batteries and computational equipment on board.

2.1 Actuation selection

In an effort to mimic the human body, the GuRoo has been built with 23 degrees of freedom. Figure 2 and Table 1 outline the location and orientation of each DoF. The actuators chosen tended towards a high torque / low speed combination to suit the anthropomorphic nature of the locomotion. In addition, no joint is required to move through more than one revolution.

The high power necessary for the lower limbs and spine was realised with brushed DC motors. For cost reasons and ease of implementation, all lower joints use the same motor / gearhead combination. The Maxon RE32 series motor wound for a nominal 32V in combination with a ceramic 156:1, 72% efficient, planetary gearhead is used. The maximum continuous output torque available is 10Nm with a maximum speed of 5.3rad/s at 2 amps of current consumption. Maximum intermittently permissible torque available is 22.5Nm at 4A. With an individual mass of 0.85kg per motor / gearhead combination, the high powered motors make up 33% of the total weight of the robot.

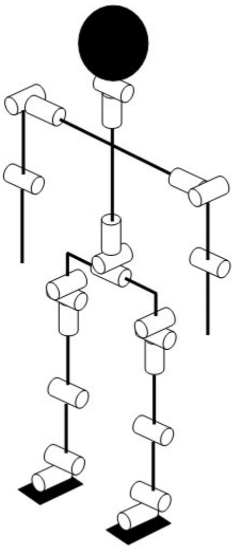

Figure 2: Location of the 23 degrees of freedom

Joint	Type	Axis	No.
Head + Neck	RC Servo	Pitch + Yaw	2
Shoulder	RC Servo	Pitch + Roll	2 x 2
Elbow	RC Servo	Pitch	2 x 2
Spine	DC Brushed	Pitch + Roll + Yaw	3
Hip	DC Brushed	Pitch + Roll + Yaw	2 x 3
Knee	DC Brushed	Pitch	2 x 1
Ankle	DC Brushed	Pitch + Roll	2 x 2
		TOTAL	23

Table 1: Type and axis of each DoF. "2 x" indicates a left and right side.

Low power, low weight and ease of controllability were the factors in choosing the actuators for the upper limbs. The RC servo motors used are Hi-Tech HS705-MG, capable of 1.4Nm output torque at speeds of 5.2 rad/s at 5V. Intrinsic metal gearboxes allow a relatively large output torque from a small package. Each servo weighs 0.125kg.

2.2 Mechanical Platform

The GuRoo stands 1.2m tall and weighs 38kgs with batteries. The supporting structure is comprised of machined 6061-T6 aluminium plate and 6063-T5 aluminium angle sections. Yaw axis motors are secured with 12mm taper locks and custom made 7075-T651 aluminium hubs. The vast majority of the structure was milled to reduce the overall weight without sacrificing significant structural stability. Sections are held together with 4mm screws and rivets therefore the robot is able to be easily disassembled for transportation. Sealed 22mm radial flanged bearings are used to support the lazy end of each joint.

The length of the DC brushed motors, at 161 mm, were a major influence in the design, resulting in the unnaturally wide legs. An anthropomorphic head, with form but no function, is provisionally used until the stereo vision and facial expression systems are complete.

As might be expected, GuRoo can only approximate many of the human movements. One of the most obvious is the crudely copied flexible spine. A human spine has 24 vertebrae distributed along the entire length that enables flexible motion, as opposed to the GuRoo who has only three orthogonal actuators. Ball joints are also present in human hips and shoulders and allow high mobility actuated from a small volume. Due to the nature of the actuators used, ball joints were difficult to implement. Instead, multiple degrees of freedom have been achieved with small sequential links. All degrees of freedom are orthogonal when the robot is in a standing position.

If the robot is un-powered and lifted off the ground, the legs will naturally swing together, as the centre of mass of the leg is outside the line of the hip joint. Additional torsion springs with a spring constant of 1Nm/degree are located in parallel with the hip roll actuators to prevent this from occuring. The springs are set such that when un-powered, the legs of the robot hang straight down. The additional torque from the spring also alleviates the stress on the hip roll motor during the single support phase of a typical walking gait.

Both Asimo and the H7 humanoids use harmonic gearheads, allowing a similar ratio to the planetary gearhead, with considerably less length and mass. WABIAN uses a non-linear spring mechanism, capable of variable impedance for each of it's 43 DoF. H6 has 33 DoF, including 7 DoF arms and a 5 DoF head. The use of these smaller and lighter actuators and construction materials, allow more degrees of freedom to be included in these robots.

3 Control Architecture

The control architecture consists of six distributed joint controller boards and either a Compaq IPAQ pocket PC or PIII Laptop as the central controller. All boards communicate according to the multi-master arrangement of the Controller Area Network (CAN). Of the six controller boards, 5 are identical, with each controlling three of the Brushed DC motors. The sixth board controls all 8 RC servo motors. All joint controllers are implemented using a TMS320F243 Digital Signal Processor from Texas Instruments.

The TMS320F243 is a 16 bit processor capable of operating at 20MHz. It can read the A/D converter, calculate a PID control law, current limit, and generate the required PWM output, in under 10 µs [5]. The IPAQ calculates the desired joint velocities for each actuator in real time and sends them serially to the servo motor board which in turn distributes messages to the CAN bus. The control architecture is shown in figure 3.

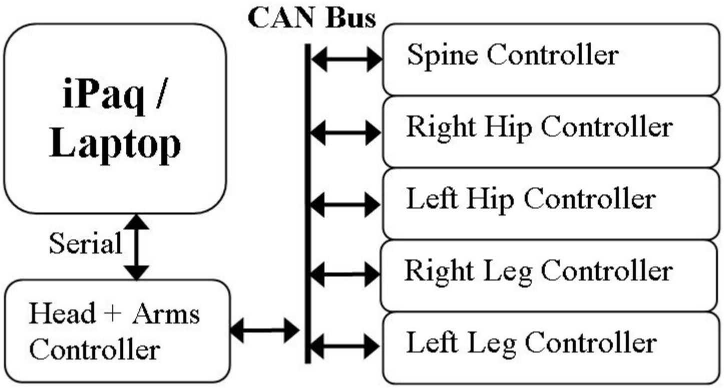

Figure 3: Distributed Control Architecture.

3.1 Networking with CAN

The Controller Area Network (CAN) is a communications system designed by Robert Bosch Gmbh for the notoriously noisy automotive environment. The CAN protocol is extremely robust with complex arbitration and inherent error checking. It can transmit at a rate of up to 1Mbit/s dependant on cable length. Unlike standard control schemes where every node is assigned a unique address, the CAN standard assigns a unique identification to each different type of packet being sent. This identifier also acts as an arbitrator, prioritising each message. Every node has a set of filters that determine whether the incoming message is carrying information relevant to the node. Message priorities are allocated such that emergency events (for example, overcurrent situations) have top priority, followed by medium priorities such as joint setpoints and low priorities such as feedback data. Each message is able to transmit 8 bytes of data with a Cyclic Redundancy Check capable of correcting up to five random errors.

The CAN network has been implemented with expansion in mind. Currently a total of five packets of desired velocities and five packets of status data are sent using the bus at a rate of 50Hz. Each packet of desired velocities contains the setpoints for 3 motors. An additional packet of velocities is sent to the servo board to control the eight degrees of freedom in the upper body. There is no feedback from these joints. Based on this information, it is possible to calculate the current CAN bus usage.

$$\begin{aligned}
\text{Motor Packet Size (bits)} &= (\text{Number of motors x 16bits}) + \text{Size of Header} \\
&= (3 \text{ x } 16) + 35 \qquad = 83 \text{ bits} \qquad (1) \\
\text{Servo packet Size (bits)} &= (\text{Number of Servos x 8bits}) + \text{Size of Header} \\
&= (8 \text{ x } 8) + 35 \qquad = 99 \text{ bits} \qquad (2) \\
\text{Total Packet Size (bits)} &= (5 \text{ x } 83) \text{ x } 2 + 99 \qquad = 929 \text{ bits} \qquad (3) \\
\text{Bus Activity @ 50Hz} &= 929 \text{ x } 50 \qquad \approx 50\text{kbit} / \text{s} \qquad (4)
\end{aligned}$$

With a maximum transmission rate of 1Mbit/s, this implies that the CAN bus is running at 5% of its capacity. This allows for that addition of extra sensor nodes of various types, including gyroscopes, accelerometers, touch sensors and information from the vision system. The daisy chain feature of the CAN protocol provides the ability to easily attach additional sensors to the system. A local microcontroller with CAN capabilities can process the sensor information and distribute meaningful information, with each data type assigned a unique identifier, recognisable by every other node in the system. By enabling the central controller to arbitrate and process the sensor information, a flexible interface with the real world can be established.

3.2 DC Motor Controllers

Control of the fifteen high powered motors is split evenly amongst five motor controller boards. Each board is responsible for the local control of 3 brushed DC motors. Each motor is driven with a L6203 motor driver, capable of sourcing up to 4A of current with appropriate thermal monitoring. Current is measured via a combination of sense resistors and amplifiers that transform the current to a voltage suitable for measurement using the microcontroller's on board analogue to digital converter. Each motor has an additional 300mH of inductance to reduce the high ripple current caused by bi-polar switching from the robot's 42V supply. Without this additional inductance, the motor's thermal dissipation is dominated by the effects of ripple current loss rather than loss from useful work.

Two external quadrature decoders operate in conjunction with the microcontroller's internal quadrature decoder to maintain feedback from the 500 count per revolution optical encoders located on each motor. By reading edges, the decoders give 2000 counts per revolution of the motor shaft, which translates to 312000 counts per revolution of the joint, or $\sim 2 \times 10^{-5}$ radians per count.

3.3 Servo Motor Controller

The eight RC servo motors are positioned by eight individual pulse length control signals from a single controller board. Each signal has a carrier frequency of 50 Hz, and is buffered through a CMOS 4024 buffer to supply 7 volts to the RC servo inputs. Each RC servo contains internal electronics and a potentiometer for local control. This internal feedback prevents the DSP from distributing the actual velocities of the upper body motors back to the central controller, or performing any form of alternate control. As such the motors are controlled by a position profile, updated at the carrier frequency of 50 Hz.

3.4 Power

The GuRoo is powered by two 42V 1.5Ah NiCad battery packs and two 7.2V 1400mAh NiCad packs on each board. The 42V packs are used in parallel as the supply for the DC motors, while the two 7.2V packs are used to power the servos and the logic respectively. The use of different power sources for different power rails prevent noise generated by the high power switching of the motors from affecting the supply for the logic circuitry. Local regulation on each board converts the 7.2V rail down to the 5V necessary for the logic circuitry.

The power board located in the rear of the torso is responsible for distributing power from the 42V packs to each motor board. Load sharing is achieved through the use of high power diodes that prevent one battery pack discharging into the other. A large 'kill switch' cuts the batteries from all boards in the event of an emergency.

3.5 Central Processing Unit

The iPAQ features a 208 MHz StrongARM microcontroller, 32 Mb of RAM and a 320 x 240 colour screen. The screen is touch sensitive allowing stylus input of text and graphics. The iPAQ in the GuRoo operates with Windows CE. It performs all the high level gait generation that is transmitted over a serial link to the servo controller board which in turn broadcasts the desired velocities on the CAN bus.

4 Software Architecture

The software comprises four major parts, the simulator, gait generation, joint controller software and low level firmware, all developed in a Visual C++ environment. The gait generation and joint control software can be compiled to either the simulator or the low level firmware to be run on the actual robot. The joint velocities required by the joint controllers are provided by the gait generator module.

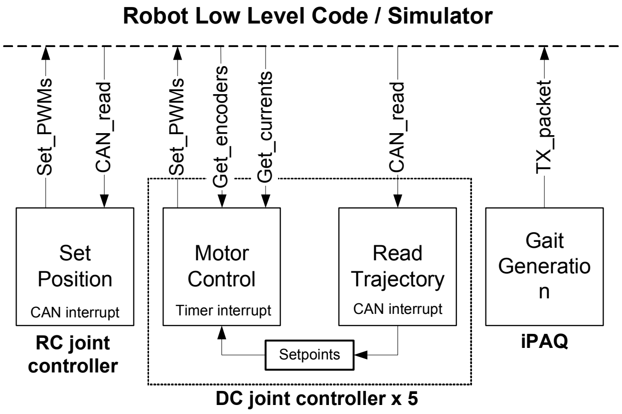

Figure 4: Block diagram of common software modules and the interface used by both the real robot and the simulator.

4.1 Gait Generation Software

The gait generation module is responsible for creating physically realisable trajectories for all 23 degrees of freedom. Trajectory planning seeks to minimise unnecessary disturbances in each joint. The walking gait is generated in real time and calculates the required velocity for all joints to perform a desired movement. Joint velocities follow a sinusoidal velocity of the form:

$$\omega = \frac{\theta}{T}\left(1 - \cos\left(\frac{2\pi t}{T}\right)\right)$$

where ω is the desired joint velocity, θ is the desired change in joint angle and T is the period of the movement. This profile ensures the joint experiences zero acceleration at the start and end of each movement which minimises the jerk and vibration. Zero velocity at the start and end of each trajectory allow for smooth transitions between trajectories. The velocity for all 23 degrees of freedom is calculated at 50Hz.

4.2 Joint Controller Software

Located in the robot are two types of joint controllers, five DC brushed motor controllers and one RC servo motor controller. The CAN interrupt routine updates the desired joint velocities. The RC controller runs a single timer interrupt routine that sets the required pulse length for each RC servo motor based on the desired joint velocity.

An interrupt driven CAN routine updates the desired joint velocity for each motor controlled by a DC motor controller. A second timer interrupt occurs at 250Hz to run the motor control routine. The actual velocity is the change in encoder readings over time. The motor control routine calculates the error between the actual velocity and the desired velocity. A PWM value is calculated from this error using a Proportional-Integral control law. The PI control terms are software based and can by adjusted dynamically at any point in the gait.

The current is measured every control loop and the PWM waveform generated is modified to keep within a software set current limit.

4.3 Humanoid Simulator

The simulator is based on DynaMechs [6], a dynamic simulation tool for multi-chained, star configured robots. It has been adapted to include specific characteristics of the GuRoo, including the distributed nature of the control architecture and the CAN bus. The GuRoo's chest is modelled as a mobile base with 5 chains arranged in a star configuration representing the arms, legs and head. The modified Denavit-Hartenburg parameters and CAD surface area provide the graphical representation of the robot as seen in Figure 5. Mass distribution information in the form of inertia tensors, is combined with actual motor characteristics to provide realistic interactions between links. Dynamechs provides the same interface as the firmware, with the ability to read encoders, measure current consumption, transmit and receive CAN packets.

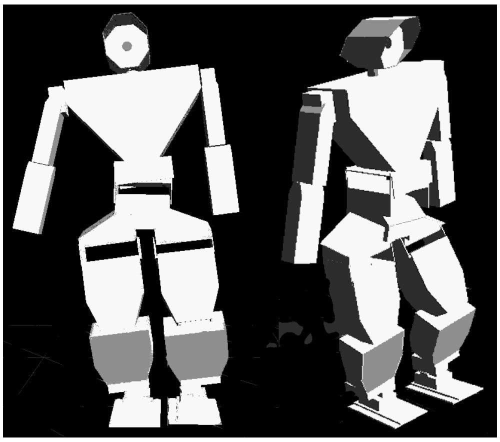

Figure 5: Dynamechs Simulator. Surface models from the CAD design and physical properties of the robot allow for accurate simulations.

4.4 Firmware

The firmware present on each joint controller board provides direct access to the sensors, motor drivers and CAN bus. The firmware is accessed by a set of generic high level functions in the Joint Control module. The nature of these generic functions allows the control code to be microcontroller independent.

5 Movements

The GuRoo performs several movements, designed to confirm the adequacy of the electro-mechanical hardware for further humanoid research. They are not performed as part of the robust walking research, but as confirmation of the robots mechanical and electrical capability. A small squat movement precedes every movement performed by the robot. An ankle pitch angle of 6 degrees is established, with the knee and hip pitch joints calculated to keep the torso upright. Pre-loading the lower body motors in this way minimises the backlash in each gearhead.

5.1 Crouching

The robot is able to perform both continuous crouching and held crouches. For each movement, a destination angle of 16 degrees is applied to the ankle pitch joint. The knee and hip pitch angle are geometrically determined to ensure the torso is kept in an upright position. One cycle of continuous crouching is performed every 7 seconds.

5.2 Standing on one leg

From a double support position, the GuRoo can stand stably on one leg for an arbitrary period of time and return to its original position. The actuation of the hip and ankle roll motors transfers the mass of the robot over either the left or right foot. The ankle pitch, knee and hip pitch motors of the non-supporting leg lift the foot 150mm from the ground. The convex hull of the supporting foot becomes the support polygon of the robot during this single support phase of the gait. The large springs located in parallel with the hip roll actuators, provide additional torque to prevent the hip link from sagging and the non-supporting leg collapsing inwards. For the robot to return to an upright position, the sequence of movements is reversed.

5.3 Open Loop Walking

The GuRoo is capable of open loop walking, based on a simplistic human walking gait. Smooth joint trajectories combined with a short stride length of 150mm minimises balance disturbances. Joint trajectories are chosen such that the torso always faces in the direction of travel, with minimal movement in either pitch, roll or yaw axis. The arms are swung to mimic human walking, but due to the low weight present, provide only aesthetics.

The roll axis motors located in the hips and ankles provide a side-to-side sway motion similar to an inverted pendulum. The amplitude of this sway motion is increased successively over three cycles until a pre-determined amplitude is reached. The period and amplitude of the sway motion is experimentally determined, and influenced by the spring damper chosen, is based on the natural frequency of an inverted pendulum model of the robot.

The supporting leg takes the weight of the entire robot at the extreme of each sway motion, when the velocity of the roll axis actuators is zero. The ankle pitch, knee and hip pitch of the non-supporting leg then lift the swing leg from the ground. The robot has entered the single support phase of the gait at the point where the foot loses contact with the ground. The springs in parallel with the hip roll motors provide extra torque to prevent the swing leg from collapsing inwards.

As the swing leg is lifted, the yaw axis of both legs turn through 16 degrees, propelling the swing leg forward. The yaw axis in the torso is actuated through -16 degrees to ensure the torso is continuously pointing forward. The double support phase of the gait is achieved when the swing leg is lowered and contact made with the ground. The hip and ankle roll motors drive the weight of the robot to the opposite side, exchanging the roles of the support and swing legs. The sequence is then repeated.

6 Results

The three movements performed, show the robots ability to perform anthropomorphic movements. By successfully crouching, the motors chosen for the lower body are justified as adequate to accelerate the mass of the robot.

The standing on one leg movement further justifies the design of the robot. The greatest static torque required by the lower motors occurs in the support leg during the single support phase of the gait. Successfully standing on one leg without the use of the current limiting system, indicates that the motors can provide sufficient torque to meet the single support phase requirements. Additionally, this movement demonstrates static stability, with the centre of mass located above the support polygon created by the contacting foot. With stable balance achieved on a single foot, it is theoretically possible for the GuRoo to perform static walking.

The open loop walking motion is an implementation of dynamic walking. From D'Alembert's Principle arises the notion of a Zero Moment Point (ZMP) introduced by Vukobratovic[7]. If the ZMP lies within the support polygon, the robot is dynamically stable. The centre of mass may not necessarily be located over the support polygon, implying the robot cannot stop at any point in its gait and remain stable. The GuRoo can walk short distances completely autonomously using the dynamic gait generated by the central controller. The walk is shaky, with balance disturbances predominantly emanating from the backlash in the gearheads. Open loop balance is achieved by experimentally tuning each joint trajectory, as global feedback is not present to compensate for these disturbances.

7 Conclusion

This paper describes the construction of the GuRoo platform. It details the completed mechanical, electro-mechanical and distributed electrical systems within the robot and outlines the software required to operate the robot. Low level firmware is implemented, allowing the individual control of all 23 actuators. The successful execution of the three anthropomorphic movements, crouching, standing on one leg and open loop walking, justifies the platforms suitability for further research into humanoid gait generation.

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