NimbRo TeenSize Team Description 2016

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Abstract. This paper describes the RoboCup Humanoid League team NimbRo TeenSize of Rheinische Friedrich-Wilhelms-Universität Bonn, Germany, as required by the RoboCup qualification procedure for the competition held from the 30th of June to the 3rd of July 2016 in Leipzig, Germany. Our team uses self-constructed robots for playing soccer. This paper describes the mechanical and electrical design of the robots, covers the software used for state estimation, computer vision and motion generation, and highlights some of our scientific achievements.

1 Introduction

Team NimbRo has had a significant amount of success in the RoboCup competition in the past years. Not only have our robots won the competitive Humanoid TeenSize soccer tournament five times in a row, but they have also proven their skills by winning the Technical Challenges, for example in 2012 and 2014. In 2015, the igus Humanoid Open Platform, which we developed together with igus GmbH, had its RoboCup debut, where it won the RoboCup Design Award. As in previous years, we have put great effort into making the walking gait of our robots more stable, especially in light of the recent changes to the surface of the RoboCup playing field, and less prone to disturbances. In the 2016

Fig. 1. Left: Team NimbRo with igus Humanoid Open Platform robots. Right: Team NimbRo's family of igus Humanoid Open Platform robots on the soccer field.

competition we want to display the advancements made in our open source ROS framework, including in the areas of attitude estimation, vision processing, localization, soccer behaviors, servo communications, and sensor management. Our software includes no software modules from other teams at this point.

2 Mechanical and Electrical Design

Fig. 1 shows our latest humanoid TeenSize robots—the igus Humanoid Open Platform. Our other previous generation humanoid TeenSize robot, Dynaped, is shown in Fig. 2. The mechanical designs of each of our robots are focused on the principles of simplicity, modularity, mechanical robustness, and low weight.

2.1 igus Humanoid Open Platform

The igus Humanoid Open Platform is the next generation of the NimbRo-OP robot [5]. It is 92 cm tall and weighs 6.6 kg. Its kinematic, electrical and sensory design is very similar to the now retired NimbRo-OP. Powered by a 4-cell LiPo battery, Robotis Dynamixel MX series actuators are used for all joints. Six MX-106 servos are used for each leg (3 in the hip, 1 in the knee and 2 in the ankle), and three MX-64 servos are used for each arm (2 in the shoulder and 1 in the elbow). Two MX-64 servos also control the pan and tilt of the head. All actuators communicate with a Robotis CM730 board, which is running a fully custom firmware. Electrically, the actuators are connected via a star topology Dynamixel bus, with both TTL and RS485 variants existing, and being supported. The CM730 incorporates 3-axis accelerometer, gyroscope and magnetometer chips, for a total of 9 axes of inertial sensory data. For visual perception, the robot is equipped with a Logitech C905 USB camera fitted with a wide-angle lens. Options for stereo vision are also supported. All mechanical parts of the robot were 3D printed out of Nylon-12 (Polyamide 12) using a Selective Laser Sintering (SLS) process. This allows for high modularity, production speed, design flexibility and aesthetic appeal. There are no further supporting elements underneath the outer plastic shell. All of the electronics and sensors are housed inside the torso, apart from the camera and USB WiFi adapter (802.11b/g/n), which are located in the head. The robot is nominally equipped with a dual-core Intel Core i7-5500U CPU, which has four logical cores and a base frequency of 2.4 GHz with Turbo Boost up to 3.0 GHz. The PC is fitted with 4 GB of

RAM and a 128 GB ADATA SX300 solid state disk. Available communication interfaces include USB 3.0, HDMI, Mini DisplayPort and Gigabit Ethernet.

2.2 Dynaped

Dynaped has long been active in the RoboCup Humanoid league, and was a core player of team NimbRo's team for many years. While the focus of development has transitioned to the igus Humanoid Open Platform, Dynaped continues to be an active soccer playing robot. Dynaped's size and weight is 109 cm and 7.5 kg respectively. The robot has 14 DoF—5 DoF per leg, 1 DoF per arm, and 2 DoF in the neck. Its main features are the effective use of parallel kinematics, coupled with high torque, provided by pairs of EX-106 actuators in a master-slave configuration in the roll and pitch joints of the hip and ankle. All other DoFs are driven by single motors.

Due to a flexible shoulder joint socketed on rubber struts and a passive protective joint in the spine, Dynaped is capable of performing a goalie dive. The torso is constructed entirely of aluminium and consists of a cylindrical tube that contains the hip-spine spring and a rectangular cage that holds the computing devices. For protection, a layer of foam was included between the outer shell and the skeleton. As of recently, work has been done to adapt Dynaped to use our ROS-based framework, with the aim of making him transparently compatible with the igus Humanoid Open Platform. He has been equipped with a modern PC (Intel Core i7-5500U) and the same type of head and camera unit. The RS-485 networked actuators are controlled through a Robotis CM740 board via a 1 MBaud serial interface. The CM740 has also been fitted and programmed to provide 9-axis IMU data for the purposes of state estimation.

Fig. 2. Dynaped

3 Perception

3.1 Proprioception

State estimation is an important topic of research in the context of humanoid soccer robots, as many types of feedback rely on it, to assist walking and kicking for example. The state estimation begins however in proper management of the IMU sensor data. The latest advances in the ROS soccer framework include the development of a scale calibration procedure for the gyroscope measurements, an online automatic recalibration scheme for the gyroscope bias, reliably producing angular drifts as low as $0.02\,^{\circ}/\mathrm{s}$, a soft iron calibration procedure for the

Fig. 3. Left: An image captured by the robot with annotation of the detected field boundary. Right: The effect of applying the undistortion model on the left image.

magnetometer, and an online hard iron offset auto-recalibration scheme for the magnetometer. With these sensor management features available, the reliability of the observed sensor measurements can be greatly increased, ready to be fused into a quaternion estimate of the orientation of the robot using the attitude estimator described in [3]. The attitude estimator was developed within the scope of the igus Humanoid Open Platform project, and is capable of combining 3-axis gyroscope, accelerometer and magnetometer data into a quaternion estimate of the total global orientation of the robot. A C++ implementation is available freely online [1]. At the core of the estimator is a nonlinear passive complementary filter that performs filtering on the special orthogonal group of rotations akin to PI control, and maintains an internal estimate of the gyroscope bias. Underpinning the attitude estimator is the development and novel mathematical formalisation of the concept of fused angles. Fused angles are a way of representing a rotation that is highly suitable for applications that relate to the balance of a body. A complete discussion of fused angles can be found in [2].

The output of the attitude estimator is combined with joint angle feedback of the servos to obtain an estimate of the global robot pose with use of a kinematic model. The joint angles are applied to the virtual model using forward kinematics, which is then rotated around the current support foot by the estimated quaternion orientation of the robot. The model is then used to extract the robot's center of mass position and velocity. With hysteresis, the support foot is taken to be the one with the lower vertical coordinate in the rotated kinematic model.

3.2 Computer Vision

Visual perception plays a significant role for successful soccer play. This task is typically divided into two parts, preprocessing and object detection. In the first part, we convert the taken image from the RGB color space to the HSV color space, due to the intuitive nature of the HSV space, and its ability to separate light and chromatic information [6]. A fixed set of camera parameters are set in the camera device to ensure short term consistency of the colors. Each robot is equipped with at least one Logitech C905 camera, fitted with a wide angle lens.

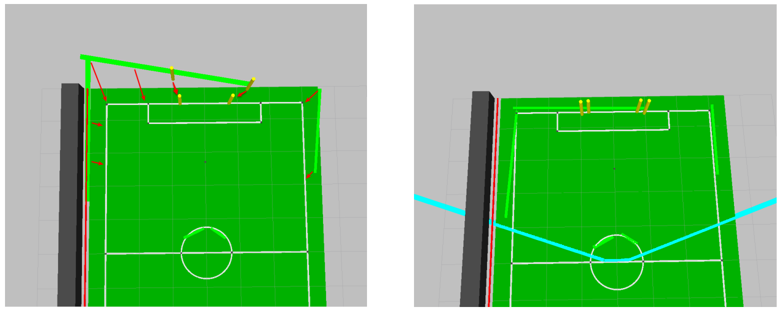

Fig. 4. Left: Projected detections prior to kinematic calibration, with projection errors annotated by red arrows. Right: Projected detections after kinematic calibration [8].

Although wide angle lenses allow more information to be perceived at once, it forces us to compensate a significant amount of distortion. We use the following pinhole camera model to compensate radial and tangential distortion. Note that the input (x, y, z) is a vector in camera frame coordinates, and the output (u, v) is the corresponding distorted pixel.

$$a = \frac{x}{z}, \quad b = \frac{y}{z}, \quad r^2 = a^2 + b^2, \tag{1}$$

$$\hat{x} = a\left(\tfrac{1+k_1r^2+k_2r^4+k_3r^6}{1+k_4r^2+k_5r^4+k_6r^6}\right) + 2p_1ab + p_2(r^2 + 2a^2), \tag{2}$$

$$\hat{y} = b\left(\tfrac{1+k_1r^2+k_2r^4+k_3r^6}{1+k_4r^2+k_5r^4+k_6r^6}\right) + 2p_2ab + p_1(r^2 + 2b^2), \tag{3}$$

$$u = c_x + f_x\hat{x}, \quad v = c_y + f_y\hat{y}, \tag{4}$$

where f_x and f_y are the focal lengths, and (c_x, c_y) is the principal point, all in pixel units. k_1 to k_6 are the radial distortion coefficients, and p_1 and p_2 are the tangential distortion coefficients. Fig. 3 illustrates the effect of undistortion on an image taken by the robot.

Using the distortion model, we can project pixels to the camera frame, but in order to project detections into egocentric coordinates, an estimate of the extrinsic camera matrix is needed. The ROS-native tf2 library [9], which can be used to manage relative transformations between coordinate frames that are attached to both the robot and its environment, is used to retrieve the transformation between the egocentric world frame and the camera frame. This information is computed in our ROS framework based on the state estimation and kinematic information. Nevertheless, although the exact kinematic model of the robot is known, some variations occur in the real hardware, often leading to large projection errors if ignored, especially in distant detected objects. To resolve this issue, we have semi-automatic calibration procedures that seek to minimize the reprojection errors using a hill-climbing method. The effect of the calibration on the projected detection distances is depicted in Fig. 4 [8].

Due to significant changes in the RoboCup rules, including the use of white goal posts, a mostly white ball, and artificial grass, for the purposes of object detection we have designed and utilize methods that are suitable for low color

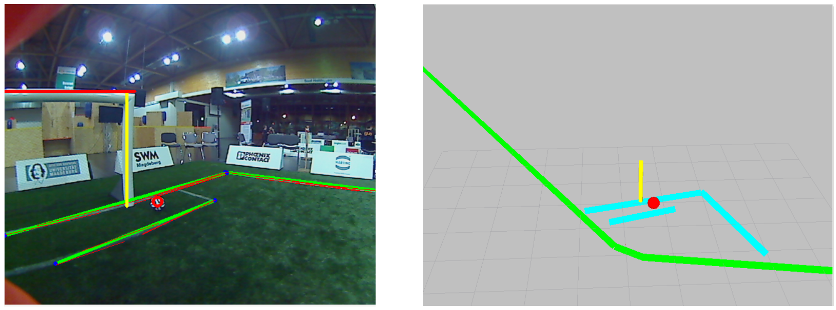

Fig. 5. Left: An image captured by the robot with annotation of the detected field lines, ball and goal post. Right: The detections projected into 3D world coordinates.

information environments. For ball and goal detection we use a histogram of oriented gradients (HOG) descriptor, which works very well for pedestrian detection [7], in the form of a cascade classifier. After gathering a number of positive and negative samples, we train the classifier with use of the AdaBoost technique. Due to the fact that HOG feature extraction is a computationally expensive procedure, using sliding windows [7] is not feasible. So, we use the descriptor only on those candidates that are preselected based on shape, size and color.

As the painted field lines on the artificial grass are no longer clear white, an edge detector is used for line detection, followed by probabilistic Hough line detection. After detecting line segments, we filter them to avoid false positives. Finally, the remaining similar line segments are merged with each other to produce fewer, larger, lines. Shorter line segments are used for detecting the field circle, while the remaining lines are passed to the localization method. A sample output for object detection is depicted in Fig. 5. Further details to the line detection can be found in [8].

3.3 Localization

A single hypothesis model is used to estimate the three-dimensional robot pose (x, y, θ) on the field. Our primary approach to overcoming sensor aliasing is by using a combination of magnetometer and integrated gyroscope values as the main source of global orientation information. We can then handle the unknown data association of ambiguous landmarks, such as goal posts and T-junctions. Over time, based on our observations, we try to update the location of the hypothesis towards an estimated position in such a way that, with consideration of noise, the hypothesis eventually points to an optimal output.

We update the location based on a probabilistic model of landmark observations involving mainly lines and goal posts [8]. The inputs to the probabilistic model come from the vision module and dead-reckoning odometry data. Currently, we are working on a full 6D pose localization approach, that makes use of 3D model-based tracking techniques.

Fig. 6. Dynamic get-up motions of the igus Humanoid Open Platform, from the prone (top row) and supine (bottom row) lying positions, and a still image of the kick motion.

4 Dynamic Robot Motions

There are numerous kinds of motions that are required in the standard repertoire of a humanoid soccer robot, but of the most fundamental are walking, kicking and getting up. In particular for the case of the latter two, it is useful to be able to express and tune such motions as a set of pose keyframes that are then automatically interpolated to become a smooth complete motion. Such motions, although predefined and for the most part fixed, can be made to be quite dynamic, in the sense that the robot is at no point statically stable during the execution of the motion. The use of feedback mechanisms on top of the hand-tuned motions further support the creation of such dynamic motions. A trajectory editor has been designed and implemented to fulfil the requirements posed by the manual design of such motions, including support for the configuration of the feedback mechanisms. Using this trajectory editor, a total of six different get-up and kicking motions were designed. In particular, in the case of the former, four different get-up motions were designed to be able to handle the various different supine and prone lying positions that occur in natural gameplay. Some of the get-up and kicking motions are pictured in Fig. 6.

In the case of walking however, keyframe motions are completely unsuitable, and somewhat more complex feedback mechanisms are required. The walking gait in use on the igus Humanoid Open Platform is based around a central pattern generated open loop gait that is an extension of the one that was used in previous work [10]. Numerous modifications were made to make the gait softer, smoother, and more able to passively dampen disturbances. Passive damping is however often not sufficient for maintaining balance, especially when walking on artificial grass, so a myriad of feedback mechanisms in both the lateral and sagittal planes were implemented based on the outputs of the state estimation. These feedback mechanisms include virtual slope walking, to avoid unexpected collisions of the foot with the ground, as well as a mix of foot angle, leg angle, hip angle, arm angle and inverse kinematics CoM position strategies. More details can be found in [4]. With these mechanisms in place, an omnidirectional gait was achieved that is able to walk on artificial grass at speeds of up to 21 cm/s.

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Team Members

Team NimbRo commits to participating in RoboCup 2016 in Leipzig and to provide a referee knowledgeable of the rules of the Humanoid League. Currently, the NimbRo soccer team consists of the following members:
Team leader: Sven Behnke
Team members: Hafez Farazi, Philipp Allgeuer, Grzegorz Ficht, Dmytro Pavlichenko and André Brandenburger

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