Online Humanoid Locomotion Control by using 3D Vision Information

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Abstract. Autonomous locomotion is one of the most important ability for humanoid utilized in human working environment. Walking control system that follows the desired motion given online is designed with layered control architecture and implemented as a basic system of autonomous walking. Moving goal tracking function and reactive obstacle avoidance function are implemented using stereo vision system as higher layers of the walking control system. Experiments using these layers are shown as basic examples of autonomous locomotion control system.

1 Introduction

Humanoid robots are considered to have the advantages of working in the environment designed for real humans because of their similar size, shape, joint arrangement, and sensor arrangement. In order to work in the environment where humans live and work, humanoid robots are required to have ability to sense and recognize the always changing environment and adapt their motion to the environment. Autonomous locomotion with the recognition of surrounding environment is one of the vital capability of humanoid that work in such environment. Sensors that can sense the environment widely is necessary for the autonomous locomotion. Stereo vision is one of the most reasonable solution for such kind of sensor.

In this paper design strategy of autonomous locomotion system is discussed. Then implementation of online control system for biped locomotion as a basic part of the autonomous locomotion system is explained. This system can handle the walking on horizontal plane that satisfies the following parameters given online: the desired direction and rotation of walking, upper body posture, and walking cycle. Then methods of utilizing stereo vision information online are explained, and experiments using stereo vision with the online walking control system are shown.
2 Online Walking Control for Autonomous Locomotion

2.1 Layered Control Approach

The ultimate goal of autonomous locomotion is that a robot goes to a destination point automatically acquiring the environment information and planning the route. In order to achieve this autonomy many kinds of technology are required such as environment map generation, localization, path planning, gait planning, reactive avoidance of obstacles, dynamical stabilization control, and motor servo control. These technologies have to work online concurrently, and they have different control cycles that depend on calculation time and update cycle of sensory information. In this paper we propose hierarchical architecture that consists of layers of different control cycles. An example of layered architecture of walking control is shown in Fig. 1. In this architecture processed result of a layer gives the control value of the next lower layer, and higher layers usually have lower control frequency. In this paper, 4 layers from the lowest, that is, Motor servo, Trajectory modification, Trajectory generation, and Gait planning, are implemented. Methods and implementations are described in the following sections. Online walking control that satisfies given direction and rotation with arbitrary upper body posture and step cycle is realized by the implemented layers. Moving goal tracking method using stereo vision that can be utilized with the implemented layers is described, and experiments on humanoid H7 are shown in section 6. Vision based reactive obstacle avoiding function that can be implemented as the next higher layer of the implemented walking control layers is also explained, and an experiment on the same humanoid is shown in section 7.

2.2 Related Works

Online Walking Pattern Generation Biped humanoids have more complicated dynamics model than biped walking robots that are developed primarily to verify walking theories. Because of the high cost of calculating the
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In recent years, several researches that realize online control of humanoid walking were reported. Setiawan, et al. realized online control of forward and backward walking by connecting motion patterns generated in advance[4]. Yokoi, et al. realized generation of online walking pattern[5] applying Three-Dimensional Linear Inverted Pendulum Mode based method[6] to humanoid type robot. Lim, et al. proposed “quasi-realtime” walking pattern generation using FFT based dynamically stable motion construction method online[7]. Honda Motor Co., Ltd. announced realtime walking pattern generation technology named “i-WALK” which uses some prediction of next movement for pattern generation[8].

We also proposed a real-time walking pattern generation method that make a humanoid to follow specified footprint locations online by dynamically stable mixture and connection of pre-designed motion trajectories[9]. However upper body motion and step cycle are limited by prepared motion trajectories. In this paper, new online walking control method is presented. This method is based on a fast generation method of motion pattern that follows desired ZMP[10]. Since what can be specified online only depends on the limitation of the adopted generation method in this case, upper body motion, step cycle, and swinging leg trajectories as well as footprint locations can be specified online. Change of dynamics model such as carrying an object can also be managed online.

Gait Planning for Biped Robots Kajita et al. realized online gait planning on biped robot that moves only in sagittal plane using ultra sonic distance sensor[11]. Lorch et al. also realized online gait planning on biped robot that moves only in sagittal plane using stereo vision sensor[12]. Yagi et al. proposed generating obstacle avoiding footprint generation method in simulation world[13,14]. We also proposed gait planning method to reach a goal position in complicated environment by connecting prepared motion segments that are both statically and dynamically stable[15]. In this paper we deal with footprint planning in horizontal plane that realizes desired motion vector.

3 Footprint Planning

Locomotion is limited in horizontal plane in this paper, and the method of generating footprints that realize desired torso movement is discussed. The movement of the torso is the half of that of the foot of swing leg in average. Then the easiest way to plan footprint is to make the movement of the foot twice as the desired torso motion in one step. However, this method turned out to generate unnatural and inefficient footprint in many cases.

Therefore we propose a new method that calculates relative landing position from the foot of the supporting leg by the desired torso movement. As
shown in Fig. 2 landing position is calculated in the coordinates whose origin is fixed at the foot of the supporting leg. When the desired torso motion in one step is \((x, y, \theta)\), that is, \(x\) (mm) forward, \(y\) (mm) leftward, \(\theta\) (deg.) turning left, the landing point is calculated in the coordinates as follows: \((x, 2y + w, \theta)\) (when swing leg is left), and \((x, 2y - w, \theta)\) (right). Here the \(x\)-axis of the coordinates is forward direction of the supporting leg foot, and \(w\) is the normal and minimum distance of two feet in sideward direction. Fig. 2 shows the examples of generated footprint using this method. In Fig. 2 (a) torso of the robot move \(a\) in forward direction in one step. It rotates \(c\) and moves neither forward nor sideward in average in Fig. 2 (b). Here \(k\) is the coefficient that increase the minimum distance of two feet in proportion to the rotation angle between the feet. In Fig. 2 (c), because of geometrical constraint feet can not cross each other in sideward direction. Then the torso motion become \(b/2\) in sideward direction. Therefore the calculated landing position was doubled only for the sideward component.

4 Online Generation of Walking Trajectory

Walking trajectory generation layer is designed to generate a trajectory that satisfies specified footprint, upper body posture, and step cycle[16]. Dynamical stability, self collision, and joint performance limitation are considered using simulation environment in this layer. In order to compensate the dynamical stability, horizontal position of upper body is modified.
Trajectory generation is carried once for a step, therefore desired motion can be specified every one step cycle. At each time a walking trajectory of 3 steps (2 steps that satisfies the current desired motion and a motion stopping step) is generated. Usually only first one step is executed and the trajectory is updated to the next one (Fig. 3). However there is a merit that the executing trajectory is always end with dynamically stable stop motion when updates of trajectory fails for some reasons. Trajectory generation of next step begin 250 (msec) before the end of the execution of the first step of current trajectory. This value is decided by maximum calculation time with some margin. The longest motion time for 3 steps is 5.2(sec), and dynamical stable pattern generation takes about 2.4% of its motion time on the computer inside the robot (Pentium III 1.1 (GHz)). As dynamically stable trajectory generation takes most of the generation time, it is difficult to repeat dynamical stability calculation in one generation. Therefore other constraints are considered in two steps, that is, a) heuristic limitation of parameters that are used for dynamically stable trajectory generation in order to extend the probability that realizable trajectory is generated, and b) validation of trajectory generated to be dynamically stable. Joint angle range, joint angle velocity, and self collision are inspected for validation. Fast distance determination method for convex polyhedra is utilized in order to conservatively guarantee that the trajectory is free of self-collision[17].

Fig. 4. Collision detection between the links of two legs. (Ankles are colliding in 4th posture, femurs, shanks, toes are colliding in 7th posture.)

5 Sensor Feedback Modification of Walking Trajectory

The role of the trajectory modification layer is to handle the disturbance caused by modelling error of the robot and environment, and quick change
Fig. 5. Trajectory of ZMP along sideward direction (left: no feedback, right: with sensor feedback)

of the environment that can not be dealt with the higher layers. We focused on dynamical stabilization in this paper. When a generated trajectory is executed without modification, our robot falls down in several steps because of the difference between real world and modelled world. We developed three control method to keep the dynamical stability of the robot. Those are:

- Modification of horizontal torso position according to the error of measured ZMP\(^{18}\) from desired one,
- Compensation of deflection around roll axis at hip joints using gyroscope sensor,
- Changing the joint servo gain according to the feet contact information in order to reduce the impact of ground reaction force.

Fig. 5 shows the sideward trajectory of ZMP and contact state of each foot for 4 step walking on the spot. First 300(msec) is the dual leg support phase(DLS), and the next 800(msec) is the single leg support phase(SLS), then the robot repeats 200(msec) DLS and 800(msec) SLS. Finally it stops walking at 4400(msec) with 300(msec) DLS. When 3 control methods are applied, the ZMP trajectory became much more closer to the planned one, and the transition of contact state was improved.

6 Tracking a Moving Goal with 3D Vision

We constructed goal tracking function as a higher layer of the basic locomotion control system in order to show an implementation of autonomous locomotion system. Moving goal tracking function consists of 3 parts, that is:

- 3D vision processing for detection and 3D position measurement in camera coordinates,
- Planning of the desired torso movement for one step,
- Camera posture control with self motion compensation.
6.1 Visual Processing

In order to acquire accurate 3D vision information, high resolution CMOS stereo camera with IEEE-1394 (Videre Mega-D: 1280x1024 pixels) is mounted on the head. As the robot and the goal are both moving, not shape but color information is utilized to detect the goal. Then the real-time depthmap generation algorithm\[19\] is employed to measure the distance of the goal. This algorithm utilizes four key issues to achieve high-speed and accuracy: 1) recursive (normalized) correlation technique, 2) cache optimization, 3) online consistency checking method, 4) applying MMX/SSE(R) multimedia instruction set. Output of this part is the 3D position of the target in camera fixed coordinates.

6.2 Planning of Torso Motion Vector

We decided to use world coordinate system to plan the desired torso motion. Torso of a biped robot does not move only along specified direction at specified speed but it also moves along other direction and the moving speed changes in order to keep dynamical stability. Therefore coordinate system fixed at the robot such as torso is not suitable for planning. World coordinate system is also convenient for utilizing the knowledge of target motion and stored map information in future extension.

The delay between image observed time and the time when it is available for processing was not negligible in our system. We estimated the delay by a simple experiment on real robot and the time was 270(msec) to 300(msec). When calculating the goal position in the world coordinates the camera position 285(msec) before the start of processing is used to compensate the delay.

The target position and the torso position at the end of the executing step is utilized to decide the desired torso motion in next one step.

6.3 Camera Direction Control

In order to keep the goal in the field of view. Camera posture is controlled by the pan and tilt joints at the neck. In order to compensate the self motion, feedforward control of camera direction to gaze a point fixed in world coordinate system during walk is realized by using the torso trajectory information. The result of the vision processing updates the gazing point represented in world coordinate system at about 10 (Hz).

6.4 Moving Ball Tracking Experiment

Moving ball following experiment was carried out as an example of the tracking of a moving goal. Fig. 6 shows the scene of the experiment. The color of the ball is pink and it is circled in the figure. The robot successfully followed the ball.
Adaptive Obstacle Avoidance with 3D Vision

Adaptive obstacle avoidance with 3D vision is implemented as a candidate of a layer that comes on top of the basic locomotion control system. Real-time Plane Segment Finder (PSF)\cite{20} is employed to distinguish floor plane and obstacles. PSF is a technology to extract plane segment from the vision information obtained by a stereo camera using 3D Hough Transformation algorithm.

This layer receives desired motion direction. If there is not enough floor plane in that direction, it modifies the motion direction. Fig. 7 shows the experiment scene of walking among obstacles. Desired walking direction is always set to forward in this experiment. Fig. 8 shows the vision processing result while walking. The robot successfully walked through among the obstacles.
Fig. 8. Processed Image of 3D Vision Information while Walking. (a: Depth map of camera view (brighter is closer), b: Camera view overlayed with the region recognized as floor plane (highlighted area), c: 3D reconstructed model, d: Direction candidates (top view))

8 Conclusion

Basic humanoid online locomotion control system that satisfies desired torso movement, upper body posture, and step cycle was designed using layer architecture, and implemented for humanoid H7. Moving goal tracking method using stereo vision while walking was developed, and moving ball tracking experiment was shown. Simple adaptive collision avoidance function with stereo vision was implemented as a candidate of a higher autonomous locomotion layer. Based on these basic autonomous locomotion system design and experiments, we are now investigating the method to organize highly autonomous locomotion system using layered architecture.

References