# Autonomous Navigation of a Humanoid Robot on Unknown Rough Terrain

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**Abstract** This paper presents an integration of laser-based perception, footstep planning, and walking control of a humanoid robot for navigation on previously unknown rough terrain. Perception system that obtains the shape of surrounding environment in a few centimeters accuracy is realized by using scanning type laser range sensor as input. A footstep planner decides the sequence of stepping positions by using the obtained terrain shape. A walking controller that can manage a few centimeters error of the terrain shape measurement is achieved by a combination of 40 [ms] cycle online walking pattern generation and a sensor feedback ground reaction force controller. An operation interface that is developed for giving commands to the robot is also presented. Mixed-reality display is adopted for realizing intuitive interfaces. Navigation system is implemented on the full-size humanoid HRP-2. Several experimental results on unknown rough terrain shows the performance of the proposed system.

## 1 Introduction

Biped robots are considered a suitable form for being used on terrains that include obstacles, discontinuous changes of height, and roughness. On the other hand, because the form is naturally unstable, making a biped robot walk through such kinds of terrain poses challenging problems. It requires an accurate perception system, a path planner that decides where to step to, and a robust walking controller.

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We succeeded in developing a walking controller of a humanoid robot that can manage the unknown roughness, such as, a few centimeter unknown change of level and 10 [deg] unknown inclination[1]. Recently small scanning-type laser range sensors that can be mounted on a humanoid robot became available and the accuracy achieved a few centimeters when observing the area of a few meters away from the robot. We utilize this good performance matching for realizing the navigation of a humanoid robot on unknown rough terrains.

Successful integrations of on-board sensing, footstep planning, and walking control were reported by using a stereo camera system[2], a laser range sensor[3], and a monocular camera[4]. The first two employed the assumption that the environment consists of horizontal plane segments in order to achieve enough accuracy of measurement that meets the capability of the walking control. The last one requires the advance knowledge about the shape of the objects in the environment. We do not use assumptions or previous knowledges of the shape of the environment in this work.

Though the shape of the surrounding environment can be obtained online in sufficient accuracy, it is hard to implement knowledges to the environment, such as, objects which are not preferred to be stepped on. In addition we do not assume the existence of the global map in this paper. We will build a interface for giving commands to the robot by using the high-level knowledge of a human operator. Outline of a path or moving direction may be the commands given to the robot, and the system plans the places to step on locally by using the obtained terrain shape. The planned footsteps can be checked through the mixed-reality interface.

Figure 1 shows the overview of the autonomous navigation system. We will explain each component technology in Section 2 to Section 5. Then the experiments on the full size humanoid HRP-2 are shown in section 6, followed by discussion and our conclusion.

## 2 Laser-based Perception System

Terrain shape map generation by using a laser range sensor is presented in this section. The terrain map for the footstep planning is represented by a grid of cells. Each cell has a height value, and also has an information value that shows whether the height of the cell is observed or not. The cell size of 0.02 [m] by 0.02 [m] is used for the system presented in this paper.

We adopted UTM-X002S (Hokuyo Automatic Co. LTD.) as a scanning-type laser range sensor. The scanning frequency is 100 [Hz] and the angular resolution is 0.625 [deg]. It can measure up to 30 [m] away. The sensor is attached to a swinging mechanism, and the mechanism is mounted on the torso of a humanoid robot as shown in Figure 2.

Obtained distance data are converted to the absolute 3D positions by using the robot position and the angle of the swinging mechanism. We are currently using an optical motion capture system (Motion Analysis Corp. Eagle Digital System) for localizing the robot in an absolute coordinate system. Then the map is updated. The newer observation replaces the height value at the corresponding cell. We employed this approach in the current implementation because of the following 2 reasons. First, it can better handle the change of the environment. Secondly, expected accuracy of the measurement relative to the robot position will be better when the point is measured from the vicinity. Adopting SLAM technologies for localizing the robot position and integrating the multiple measurement for realizing better accuracy are the next topics we are going to work on.

An experiment of obtaining a terrain map on the flat office floor while standing still was carried out as an evaluation of accuracy. Figure 3 (left) shows the experimental setup. The map region is limited to the light blue area of the floor (5 [m] x 5 [m] rectangle). The sensor swung between 15 [deg] and 90 [deg] from the horizontal plane. It took 2 [s] for each upward and downward scan. Obtained map is shown in Figure 3 (right). Two sets of arrows show the left and right foot positions, and yellow area indicates the cells whose height has not been obtained. Figure 4 shows the height error of the map to the distance from the laser range sensor.

Figure 5 shows an example of the obtained map for a complex terrain. Obtained terrain map after walking though the terrain is overlayed to a ceiling camera view in the right image.

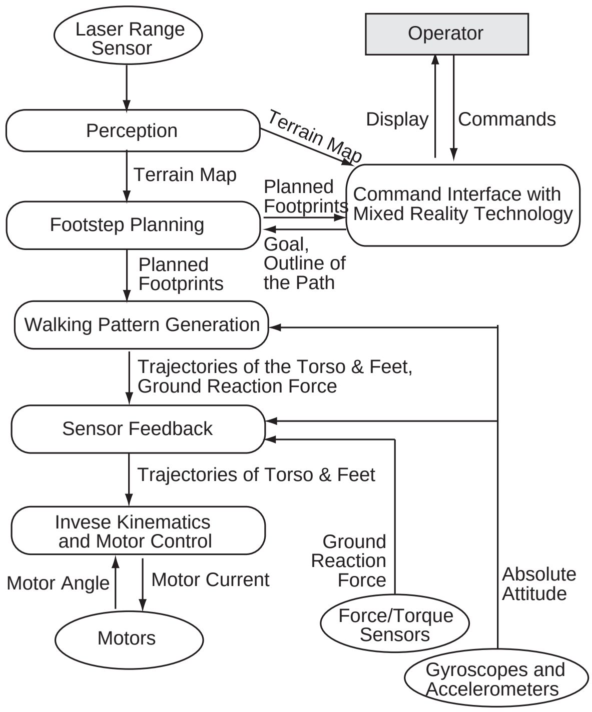


**Fig. 1** Overview of the Autonomous Navigation System

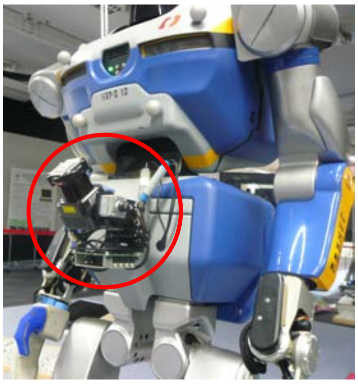

**Fig. 2** Scanning-type Laser Range Sensor with a Swinging Mechanism Mounted on the Torso of a Robot

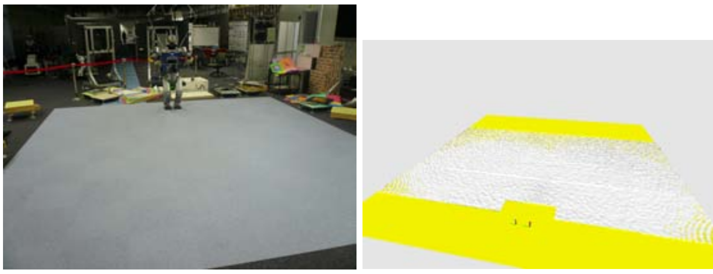

**Fig. 3** Evaluation of the Terrain Shape Measurement. (Left: A Snapshot of the Experimental Setup, Right: Obtained Terrain Map)

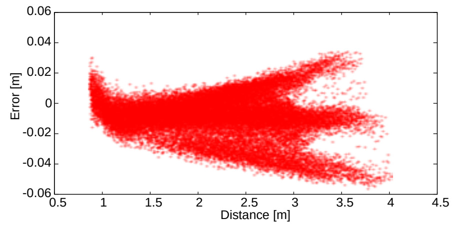


**Fig. 4** Distribution of Height Error for Terrain Map Acquisition

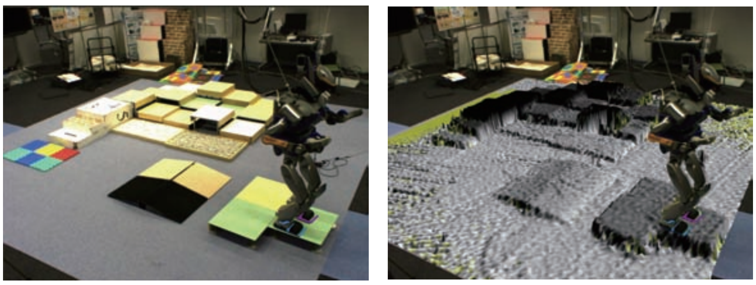

**Fig. 5** An Example of Acquisition of a Terrain Map for a Complex Environment

## 3 Footstep Planning

Footstep planner uses an A* search to generate a sequence of footstep locations to reach a given goal state. Possible foot transitions are limited to a finite number by limiting the landing positions of swing foot relative to the stance foot. An Example of a limited transition set is shown in Figure 6. The figure is shown in top view, and the gray foot shows the left stance foot. Possible landing positions of the right foot are shown as white rectangles. The terrain shape of the stepping position is evaluated. Then whether the robot can step on is judged and the quality of the position is calculated as a location's cost. Inclination of the terrain, "roughness", "stability", "largest bump", and "safety" are used as metrics for both the judgment and the cost calculation.[5]

Using the fewer number of possible transitions as a candidate set is effective for making the planner online use. On the other hand, if the possible transitions are too limited, it fails in finding a sequence of footprints that traverses rough terrain since the possible landing position is also limited by the terrain shape. We proposed "adaptive action model" for solving this problem[6]. Basic idea is trying to keep the number of possible transitions even on the rough terrain. If a possible transition is not valid because of the terrain shape, an appropriate transition near the original position is searched for as an alternative position. This method generates a suitable landing position candidates that fit to the given terrain shape.

We prefer to give not only the goal but also outline of the path in some cases, so that the operator's knowledge and intention can be transferred to the navigation system more clearly. We built a path planner that takes guide curve into consideration[7]. A heuristic for the A* search is generated from the guide curve so that the search will be carried out along the curve.

Free leg trajectories that will not hit the terrain while moving are planned after the decision of the sequence of the footprints.

**Fig. 6** Examples of Transition Sets for Footstep Planning

# 4 Walking Control

The requirements for walking controller as a part of the autonomous navigation system are realizing footprints and free leg trajectory given online by the footstep planner and managing the error of the terrain shape which is caused by the perception system.

Humanoid walking was commonly realized by constructing a dynamically stable trajectory in advance by using dynamics parameters and executing this trajectory with sensor feedback, if needed. This procedure was adopted because bipedal humanoids have a complicated dynamic model.

In recent years, several studies on the online generation of dynamically stable walking patterns have been published (e.g., [8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18]). We extended this approach and constructed a system that generates walking patterns at very high frequency, such as a 40 [ms] cycle, and which considers the actual motion of the robot as the initial condition of each generation. Maintenance of the dynamical stability of actual walking is realized by this frequent generation from the actual motion conditions. We achieved an walking controller that can handle a few centimeter unknown change of level or 10 [deg] unknown inclination by combining the high frequency generation system with a sensor feedback ground reaction force controller[1]. This controller is adopted for realizing footprints given online and managing the perception error.

## *4.1 Dynamically Stable Pattern Generation*

Figure 7 shows the overview of the dynamically-stable trajectory-generation system. The role of this part is generating a dynamically-stable walking trajectories that connect from the estimated motion status.

Since the trajectory generation takes some time (We currently start each generation at 36 [ms] before the starting time of 40 [ms]-trajectory length), the initial condition at the future moment should be estimated by using the current motion status. Let $t_n^{ini}$ and $t_n^{est} = t_n^{ini} - T_{est}$ be the start time of the $n$-th motion and the time of decision for the $n$-th initial condition, respectively ($T_{est} = 0.036$[s] in the current implementation). The initial position of the torso in the transformation matrix representation of the $n$-th trajectory is decided by using the estimated absolute position of the torso at $t_n^{est}$ (${}_wT^t_{est}(t_n^{est})$), as follows;

$$ {}_wT^t_n(t_n^{ini}) = {}_wT^t_{est}(t_n^{est}) \left({}_wT^t_{n-1}(t_n^{est})\right)^{-1} {}_wT^t_{n-1}(t_n^{ini}) \tag{1} $$

The initial positions of the left and right feet are decided in the same manner.

Trajectories for the horizontal torso position are used for maintaining balance. Foot position and posture trajectories and torso height and posture trajectories ($\mathbf{s}(t)$ in Figure 7) are designed to follow the given command smoothly from the estimated initial conditions.

The initial position of the center of mass is calculated from the estimated initial torso and foot positions (${}_wT_n^t(t_n^{ini})$, ${}_wT_n^l(t_n^{ini})$,${}_wT_n^r(t_n^{ini})$). Then the desired center of the mass (CM) trajectory is generated from the reference ZMP trajectory by applying preview control theory[19]. The desired CM trajectory is converted to a horizontal torso position trajectory by applying a slightly modified version of the resolved momentum control method [20]. Here, trajectories of the feet and other components of the torso are used for deciding the horizontal torso position.

Finally inverse dynamics calculations are carried out to decide the desired ground reaction force necessary to execute the generated motion. The calculated ground reaction force will be the control reference of the sensor feedback part of the system.

## 4.2 Sensor Feedback Modification

The goal of this part is to realize the specified torso motion in the absolute coordinate system for a short-term timescale even if the terrain shape is different from the expected one. Gradual divergence from the given trajectories will not be a big

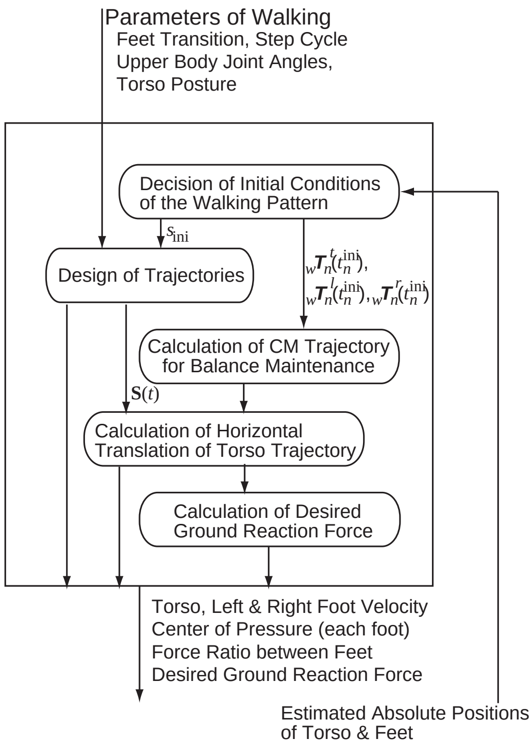


**Fig. 7** Overview of the Dynamically Stable Trajectory Generation

problem as the repetitive trajectory generation compensates for the divergence by using the actual motion for the initial conditions. We basically adopted two kinds of feedback control in this part. One kind of feedback control is ground reaction force control. In order to make the torso motion insensitive to the difference of the terrain shape, we try not to control foot positions but the ground reaction force at the feet. The other kind of feedback control is the control of the absolute posture of the torso.

Figure 8 shows the overview of the sensor feedback control system. The estimate of the position and posture in the absolute coordinate system is carried out in this loop at a 1 [ms] cycle. The estimated information is used for deciding the orientation of the coordinate system, which is used for the ground reaction force control, as well as sent to the trajectory generation system.

Ground reaction force control is implemented as a damping control of the foot positions. The input of the control is the desired reaction force and velocity. The desired velocity of the feet given from the trajectory generation system is modified according to the ground contact phase. Then the given ground reaction force is also modified according to the error of torso angular velocity. This works as the torso posture damping control, and tries to maintain the torso posture as specified by the trajectory generation system. Finally the damping control is carried out using the desired center of pressure point as the control point, and the desired foot positions are decided.

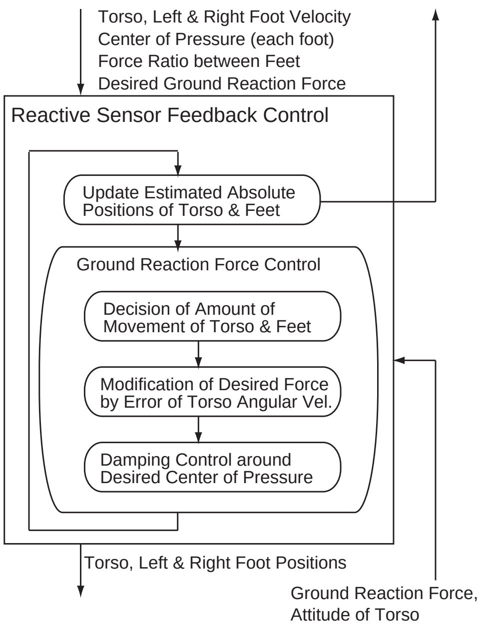


**Fig. 8** Overview of the Sensor Feedback Control System

## 5 Operation Interface

Three different operation interfaces for giving commands to the autonomous navigation system are presented in this section.

### 5.1 GUI Interface

The most basic interface is specifying the goal on the obtained terrain map by using a GUI interface (Figure 9 (c). Corresponding experimental setup is shown in Figure 9 (a)). Outline of the path can also be specified by using this interface (Figure 9 (d). Corresponding experimental setup is shown in Figure 9 (b)). The operator's knowledge of the terrain and the preference of the route can be transfered to the navigation system by giving the outline of the path. A problem of this interface is that the goal may be in the area where the terrain shape has not been obtained as shown in Figure 9. The operator needs to know the target environment by other means and the correspondence to the map shown in the GUI system.

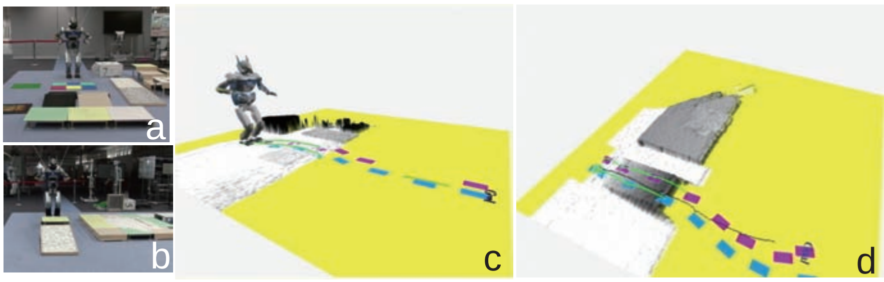


**Fig. 9** a GUI Interface for Navigation Control

**Fig. 10** a Mixed-Reality Interface for Navigation Control

### 5.2 MR Interactive Interface

The second interface is a mixed-reality interface. The operator wears a head mounted display (HMD) and uses a game controller (controller). Positions of both the HMD and the controller are localized by the optical motion capture system in the same absolute coordinate system as the robot is localized. The operator can draw an outline of a path or specify a goal by using the controller, and the drawn path and the goal is overlayed to the HMD view as well as the planned path (Figure 10). Commands to the robot, such as, start walk, can be given in the same interface as shown in Figure 10 (right). The operator can specify the goal or the outline path intuitively even if the target position is not yet observed by the perception system. A drawback of this interface is that the operator has to be in the operation area to specify the positions.

### 5.3 Joystick Interface

In order to overcome the drawback of the previous interface, another mixed-reality interface is introduced. The robot's camera view is displayed in the monitor screen and the desired direction and rotation of locomotion is given by manipulating the triangle shape in the view using a joystick (Figure 11). The usage of the footstep planner is changed from the global path planning to the local path planning. It plans a few step sequence that realizes the desired movement as well as adaptation to the local terrain shape. The interface realized the remote control of the autonomous locomotion. However a drawback is that the operator has to get more involved with the locomotion control.

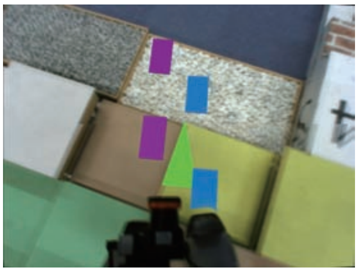

**Fig. 11** a Joystick Interface for Navigation Control

## 6 Experiments

We implemented the proposed control system on the full-size 38 DOF humanoid, HRP-2. Terrain map building and footstep planning were carried out on a computer outside of the robot and laser range sensor data and the planned result were sent from/to the robot via Ethernet. At every step the robot makes, the the planner begins computing a new plan based on the robot's position and the step it is executing. By computing a new plan at each step, the robot can use the recent perception results and adjust slips, or other deviations from the plan. Footstep planning is repeated more frequently for the joystick interface in order to achive better response to the change of the joystick input.

We installed a Core 2 3.06 [GHz] CPU board on the robot. The dynamically-stable walking pattern generation, sensor feedback control, were implemented on the CPU together with sensor processing and motor servo control. The dynamically-stable trajectory generation runs at 40 [ms] cycles and takes about 30 [ms] for generating a pattern 40 [ms] in length. At the same time, the sensor feedback control runs at a 1 [ms] cycle for executing the generated trajectories.

Snapshots from experiments of autonomous navigation on previously unknown rough terrains are shown in Figures 12, 13, and 14. Each experiment uses different interface system described in the previous session.

Pebbles are put on the slope in the experiment shown in Figure 12. The GUI interface is used for giving the commands. The GUI view is superimposed in the top left of each snapshot. Yellow area means that the height is unknown. Since the operator knew the environment, he drew an outline of the path including the area where the height is unknown. The terrain map was incrementally built while walking, and the obtained map was used online for planning the footprints that fit to the terrain. Online incremental map building and replanning worked well, and the robot successfully reached the goal approximately following the given outline.

Figure 12 shows the case in which mixed-reality interface was used. The operator's view given by the HMD is shown in the first four snapshots and superimposed at top right position in each other snapshot. The view superimposed at the bottom right from the fifth snapshots shows a obtained terrain map overlayed on the ceiling camera view. The robot successfully walked through the previously unknown rough terrain by following the given outline approximately.

An autonomous navigation experiment with the joystick interface is shown in Figure 14. The view shown to the operator is superimposed at the top left of the snapshots. The green triangle mark indicates the commanded direction and rotation. Obtained map and planned footprints projected on the map are shown in the button left of the snapshots. The operator successfully guided the robot by the joystick interface just watching the top left view.

## 7 Conclusion

An integration of online perception, footstep planning, and walking control of a humanoid robot for navigating on previously unknown rough terrains was presented. A laser-based perception system realized the online measurement of the surrounding terrain shape in a few centimeter accuracy. Using it with the robust walking controller that can manage a few centimeter unknown roughness realized a navigation system on previously unknown rough terrains. Operation interfaces that uses mixed-reality display enabled us to give our intention to the system by intuitive commands.

Localizing the robot by using its odometry and laser sensor data is the next topic that we are working on. Building and using larger-scale map is another future topic.

**Fig. 12** Snapshots from an Experiment of Autonomous Navigation on Unknown Terrain (GUI Interface)

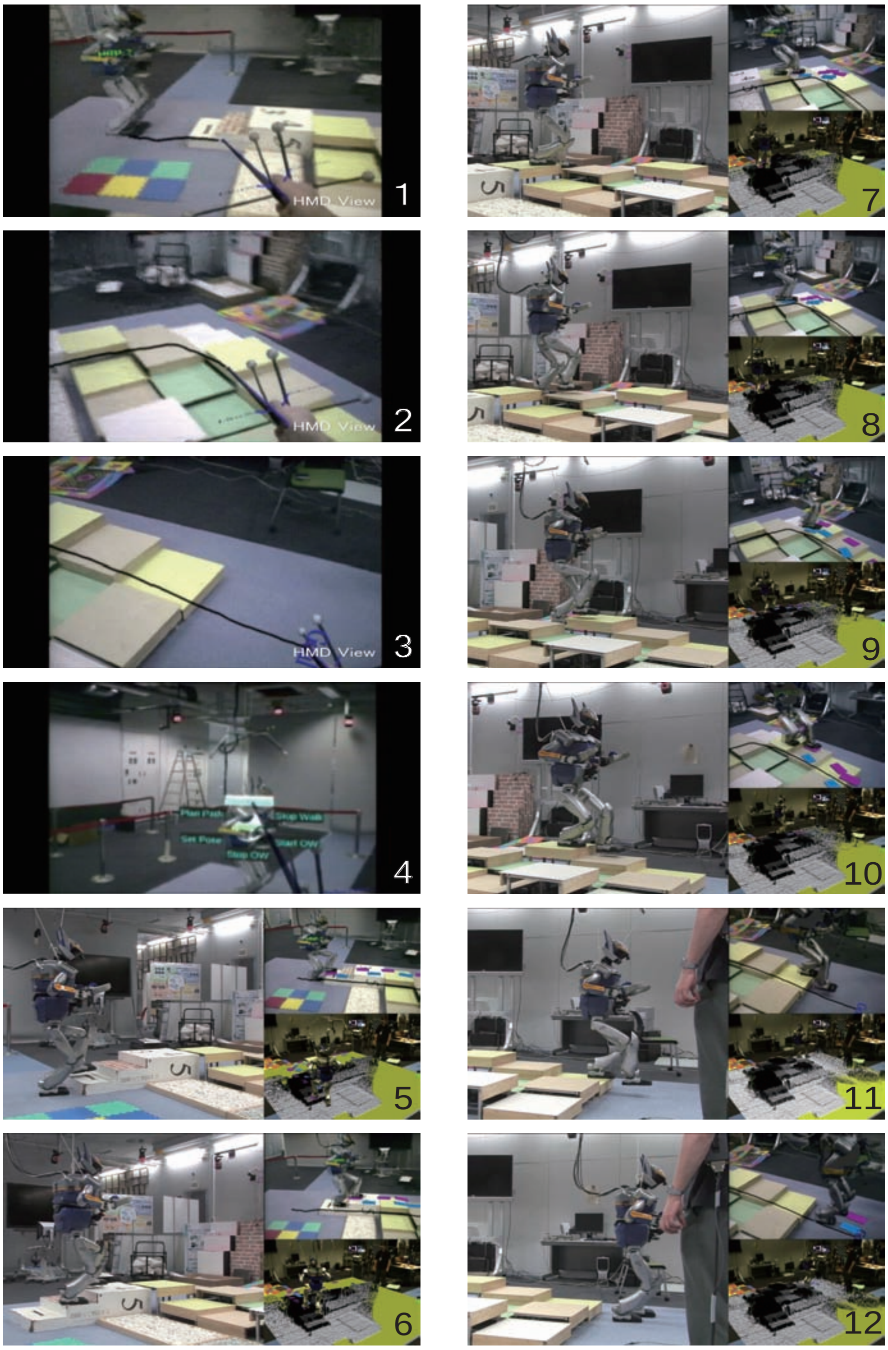


**Fig. 13** Snapshots from an Experiment of Autonomous Navigation on Unknown Terrain (Mixed-Reality Interface)

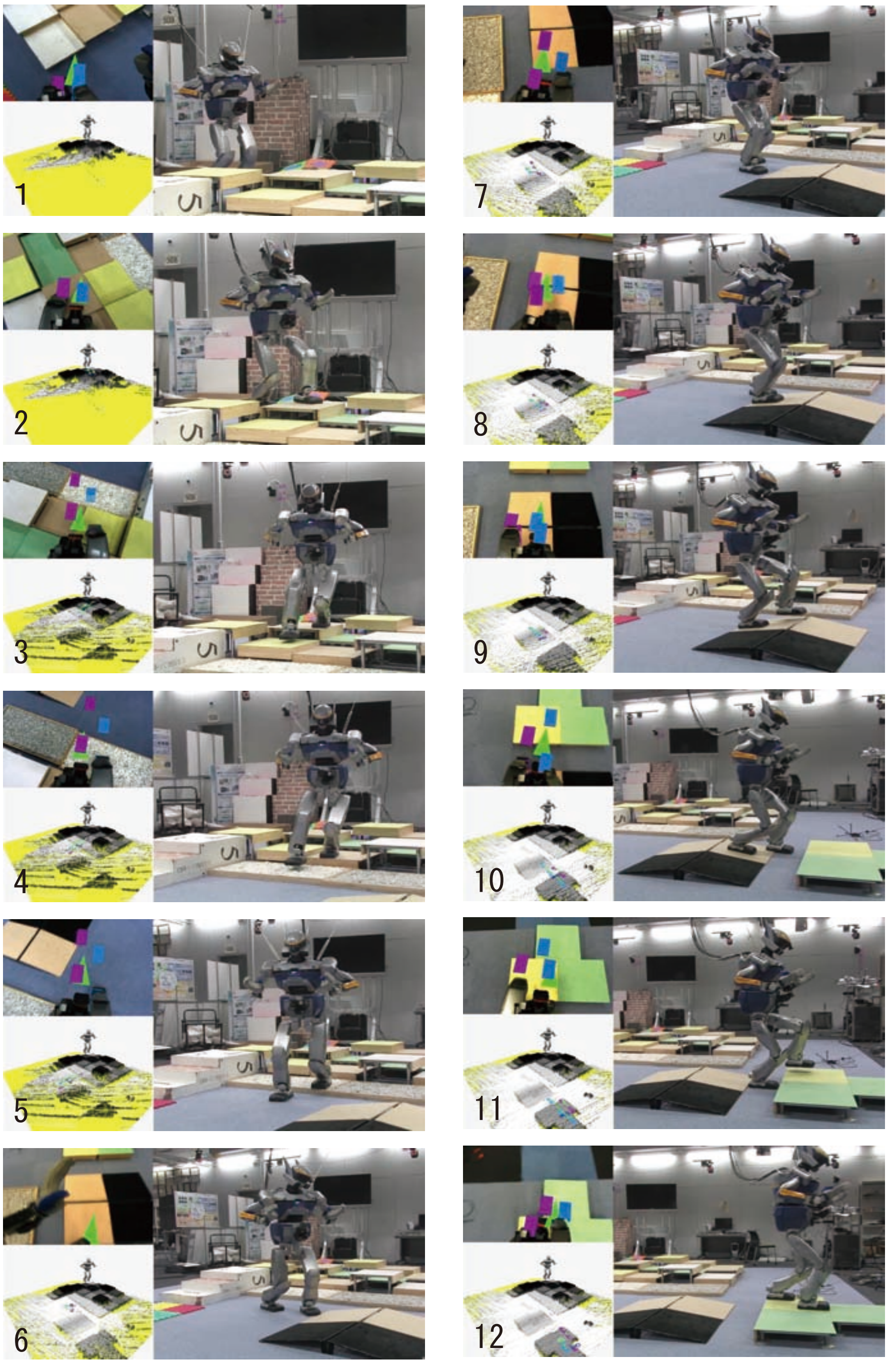


**Fig. 14** Snapshots from an Experiment of Autonomous Navigation on Unknown Terrain (Joystick Interface)

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