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Development of a Contact Interaction-Based Navigation Strategy for a Biped Humanoid Robot

Hanafiah Yussof, *Member, IEEE,* Mitsuhiro Yamano, Masahiro Ohka and Yasuo Nasu

Abstract— **This paper presents the development of a contact interaction-based navigation strategy for a biped humanoid robot with the aim of supporting current visual-based navigation. The robot arms are equipped with force sensors to detect physical contact with objects. We proposed a motion algorithm consisting of searching tasks, self-localization, correction of locomotion direction and obstacle avoidance. Priority is given to right-side direction to navigate the robot locomotion in conjunction with a strategy to avoid obstacles. The proposed algorithm is evaluated in an experiment with a humanoid robot operating in a room with walls and obstacles. The experimental results reveal good performance of the robot when recognizing objects by touching and grasping, continuously generating suitable trajectory to correct locomotion direction and avoiding collisions.**

I. INTRODUCTION

RESEARCH on humanoid robots in areas related with human-robot interaction has rapidly increased recently especially for application to human living environments and emergency sites [1][2]. It is apparent that the environments to be shared by humanoid robots are normally dedicated to humans. Therefore, to effectively work and cooperate with humans, humanoid robots must display abilities and skills that are compatible with those of humans. Indeed, the collaboration of humans and robots will impose on the robots with their mechanical-control structure the requirement to perform tasks in environments with obstacles. Hence, it is necessary for the robots to incorporate a reliable navigation strategy in order to effectively recognize the environment in which they operate and to avoid collisions.

In robot systems, navigation is a complex behavior, particularly for biped walking robots. To realize the robot in the real-world, a sensor based navigation function is required because the robot is not able to autonomously operate based on environment recognition alone. The many types of sensors that have been used in navigation tasks so far can be categorized into two types: non-contact sensors such as vision sensors and laser range sensors, and contact-based sensors such as force sensors and tactile sensors.

Hanafiah Yussof and Masahiro Ohka are with the Graduate School of Information Science, Nagoya University, Furo-cho Chikusa-ku Nagoya 464-8601 Japan (phone: +81-52-789-4251; fax: +81-52-789-4800; e-mail: Hanafiah: hanafiah@nuem.nagoya-u.ac.jp, Ohka: ohka@is.nagoya-u.ac.jp)

Mitsuhiro Yamano and Yasuo Nasu are with the Faculty of Engineering, Yamagata University, Jonan 4-3-16 Yonezawa Yamagata 992-8510 Japan (e-mail: Yamano: yamano@yz.yamagata-u.ac.jp, Nasu: rin_nasu@ybb.ne.jp)
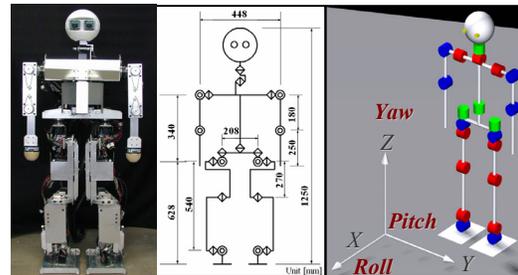
Fig. 1. Humanoid robot Bonten-Maru II and configuration of dofs.

In normal conditions, it is obvious that a navigation system that applies non-contact sensors provides intensive information about the environment [3]. However, robots cannot just rely on this type of sensing information to effectively work and cooperate with humans. For instance, in real applications the robots are likely to be required to operate in areas where vision information is very limited, such as in a dark room or during a rescue mission at an earthquake site [4]. Moreover vision sensors have significant measurement accuracy problems resulting from technical problems such as low camera resolution and the dependence of stereo algorithms on specific image characteristics. Furthermore, the cameras are normally located at considerable distance from objects in the environment where operation takes place, resulting in approximate information of the environment. In addition to the above, a laser range finder has also been applied in a robot navigation system [5]. This sensor is capable of producing precise distance information and provides more accurate measurements compared with the vision sensor. However, it is impractical to embed this type of sensor with its vision analysis system in a walking robot system because of its size and weight [6].

A navigation system that applies contact-based sensors is capable of solving the above problems, particularly for a biped walking robot system [7]. This type of sensor can accurately gauge the structure of the environment, thus making it suitable to support current navigation systems that utilize non-contact sensors. Furthermore, the system architecture is simpler and can easily be mounted on the walking robot body. However, in order to effectively navigate robot locomotion based on this type of sensing information, it is necessary to develop a reliable navigation strategy in the robot control system. In this research, we utilized a prototype 21-dofs humanoid robot called Bonten-Maru II, as shown in Fig. 1. We analyzed the robot's locomotion functions based on contact interaction of the robot arms with objects.

II. Purpose and Methodology

Humanoid robots are the type of robot that is practically suited to coexist with humans because of their anthropomorphism, human friendly design and locomotion ability [8].The application of the humanoid robots in the same workspace as humans will inevitably result in contact interaction. Besides visual data that provides intensive information on the environment structure, a system on the robot's surface is required so that the robot can detect physical contact and gauge the structure of its environment, particularly when the vision sensor is ineffective.

In this research, with the aim of supporting current visual-based navigation, we develop a basic contact interaction-based navigation strategy for biped humanoid robots capable of performing self-localization and obstacle avoidance tasks. The proposed navigation strategy requires that four main tasks be solved: searching tasks, self-localization, correction of locomotion direction and obstacle avoidance. This system is based on the contact interaction of the robot arms with objects. Our goal is to create suitable algorithms for humanoid robots to effectively operate in environments where visual information is not available. In order to make a humanoid robot recognize its surrounding, six-axis force sensors were attached at both robotic arms as end effectors for force control. The force sensor is capable of detecting three force components in each axial direction with high accuracy.

III. State-of-the-Art Survey of Robot Navigation

A robotic system performing a navigation task must have the ability to move itself from an initial position to a desired one. Basically, the navigation system encompasses such subcomponents as sensing, localization, obstacle avoidance, path planning and path execution. Our survey of journals and technical papers resulted in finding only a very small number of works reporting the navigation strategy for a biped humanoid robot [6][9]. Most reports are related to applications involving mobile robots and humanoids on a static platform [3][10][11]. This current state of research is probably due to the complexity of the biped locomotion of a humanoid robot that involves trunk movement and stability issues. Moreover, only a small number of achievements are reported relating to navigation applying contact-based sensors [7]. Most reports are related to perception-guided navigation, dealing particularly with visual-based navigation [12] and application of a laser range sensor [5].

Related with navigation strategy in a robot system, several approaches such as a mapping strategy [13], application of collision prediction functions [14] and on-line learning strategy [15] are been used. However, in this research, we focus in real-time motion trajectory generation in biped walking robot based on contact interaction information of the robot arms with objects. Despite the lack of achievements in the contact interaction-based navigation for humanoid robots, we believe that contact-based navigation is one of the most important functions to support current navigation systems.
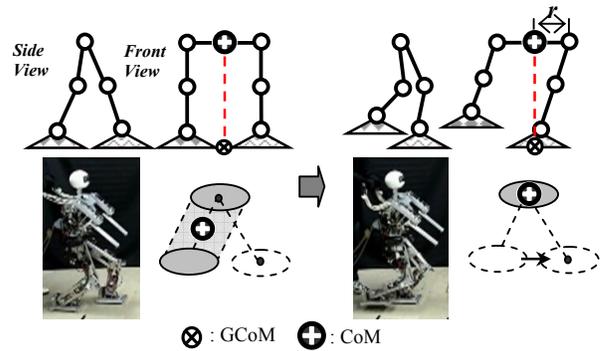
Fig. 2. Static walking model for biped robot.

IV. Consideration of Biped Walking Characteristics

One of the most sophisticated forms of legged motion is that of biped gait locomotion. As the biped walking pattern will greatly influence in humanoid robot navigation, it is worthwhile taking a brief look at the biped locomotion characteristic.

Human locomotion stands out among other forms of biped locomotion chiefly in terms of the dynamic systems point of view. This is due to the fact that during a significant part of the human walking motion, the moving body is not in static equilibrium. In contrast, for a biped robot two different situations arise in sequence during the walking motion: the statically stable double-support phase in which the whole structure of the robot is supported on both feet simultaneously, and the statically unstable single-support phase when only one foot is in contact with the ground, while the other foot is being transferred from back to front.

It is understood that to realize a stable gait motion, Center of Mass (CoM) and Ground Projection of Center of Mass (GCoM) must be in straight line where the GCoM must always be within the foot sole area, as shown in Fig. 2. If GCoM is outside of the foot sole area, the robot will lose balance and fall down. Notice that when swinging one leg, the waist moves to be on top of another leg in order to shift CoM position so that the CoM is centered with the GCoM. These movements bring together the whole robot trunk to left and right simultaneously. In order to safely navigate the biped locomotion in a humanoid robot, it is necessary to consider the trunk movement of the robot body. In this study, the trunk movement is considered as a parameter value r, which is taken as the distance from waist-joint to hip-joint.

V. Navigation Strategy and Motion Algorithm

In the proposed humanoid robot navigation strategy, we create a motion algorithm consisting of four important processes: searching process, self-localization by grasping, correction of locomotion direction and obstacle avoidance. The algorithm flowchart is shown in Fig. 3. The algorithm comprises formulations of kinematics solutions, interpolation of manipulator end-effector, and force-position control in order to generate trajectory for each robotic joint [16].
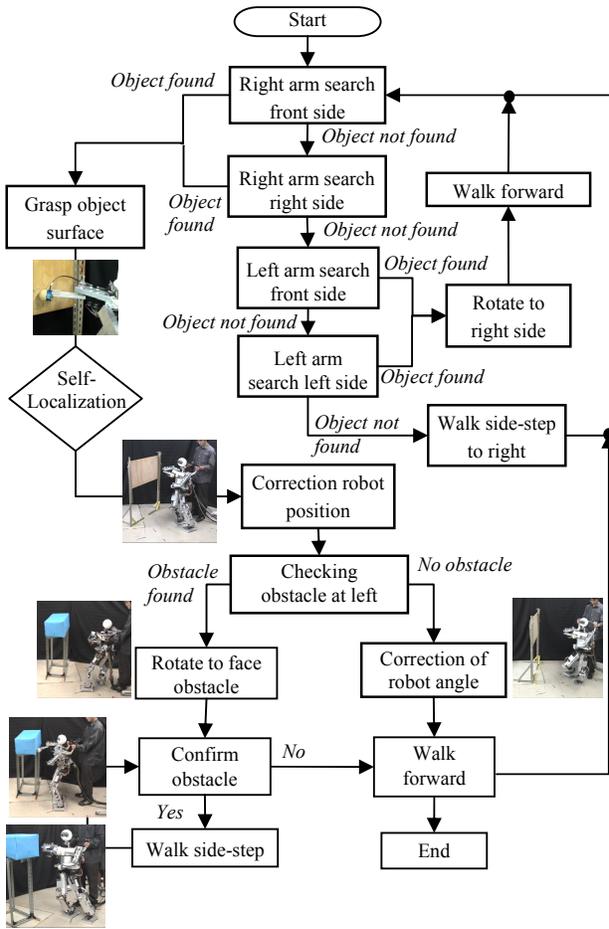
Fig. 3. Contact interaction-based navigation algorithm.

Fig. 4. Structural dimensions, search and detection area of the robot's arm.

A. Searching Process

The searching process to find objects is performed in sequence using both robots' arms which mounted with force sensors as end-effector for force control. During the searching process, the motion will stop when the arm end-effector touches an object and the force detected exceeds the maximum force parameter value. At this point, each encoder at the arm joints will record angle data and by solving direct kinematics calculation of the joint angles, the end-effector position will be obtained.

Figure 4 shows the searching and detection area of both arms. The detection range covers the robot front, right and left side within the arms' reaching range. In order to effectively navigate robot locomotion, and at the same time simplify the navigation tasks, detection motion priority is given to the right arm to lead the searching process. Basically, the right arm's function is to search for objects, grasp them to define self-localization, and confirm the presence of obstacles. The left arm functions as an obstacle checker to navigate the robot, either to correct its orientation or to perform obstacle avoidance. During the searching process, in cases where the object is detected only by the left arm, the robot will turn to its right side and repeat the search and detection process. By applying this method, intelligent detection of most objects

around the robot can be demonstrated. In addition, this method provides reliable relationships between self-localization and obstacle avoidance. At this current stage, object detection is limited to a solid object with a flat surface and the height is about the same as the height of the robot.

B. Self-Localization

It is important for the robot to at first recognize its position and orientation within the environment in which it operates before performing the navigation tasks. This process is called self-localization. In the proposed navigation strategy, self-localization is performed by grasping an object surface to define orientation of the grasped object. Based on this information, relative relations of distance and angle between the robot and the object can be defined.

During the grasping process, the position of the arm's end-effector is defined by performing kinematical calculations [16]. Whereas, the grasping movement of the end-effector on the object surface is controlled using force-position formulations based on force information obtained by the force sensor. In these formulations, we applied parameters of maximum force F_{max}, minimum force F_{min} and arm's end-effector's shifted distance in one sampling time l. This is to control the contact pressure and movement of the end effector on the object surface. Here, the reference position or the targeted point of the end effector is described as P_{ref}, whereas the current position is described as P_{cur}. Based on the detected force F which is controlled by the above mentioned parameters, the end effector's targeted position P_{ref} in regard to global axes X-Y-Z is defined from the end effector's current position P_{cur} in one sampling time. The force-position controls are explained as follows:

- For grasping object at front position:

$$P_{ref} = P_{cur}\text{-}l_x, \text{ when } F > F_{max} \tag{1}$$
$$P_{ref} = P_{cur}\text{-}l_y, \text{ when } F_{min} \leq F \leq F_{max} \tag{2}$$
$$P_{ref} = P_{cur}\text{-}l_x, P_{ref} = P_{cur}\text{-}l_y, \text{ when } F < F_{min} \tag{3}$$

- For grasping object at right-side position:

$$P_{ref} = P_{cur}\text{-}l_x, P_{ref} = P_{cur} + l_y, \text{ when } F > F_{max} \tag{4}$$
$$P_{ref} = P_{cur}\text{-}l_x, \text{ when } F_{min} \leq F \leq F_{max} \tag{5}$$
$$P_{ref} = P_{cur}\text{-}l_y, \text{ when } F < F_{min} \tag{6}$$

Figure 5 shows the robot arm performing a grasping motion. The arm's end-effector position data were saved and compiled in the robot control system, as shown in the graph of Fig. 6. This figure also indicates the geometrical analysis of the robot position and angle after the grasping process.
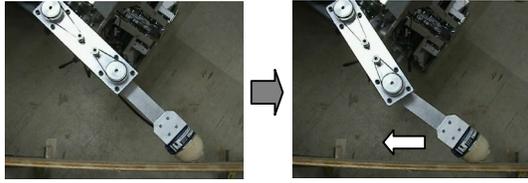
Fig. 5. Robot arm during grasping on object surface.

Fig. 7. Correction of distance and angle after grasping front object.
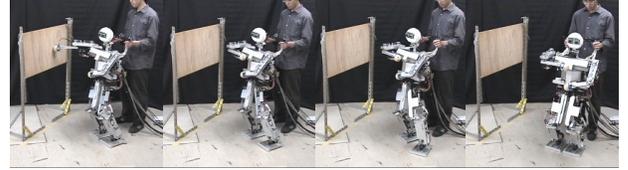
Fig. 8. Correction of distance and angle after grasping right-side object.

Fig. 6. Result for grasping right-side object and geometrical analysis after the grasping process.

The position data are calculated with the least-square method to result in a linear equation as shown in (7). A straight line from the reference coordinates origin and perpendicular with (7), which described the shortest distance from robot to wall, is defined in (8). Consequently, the intersection coordinate at X-Y axes plane is defined in (9). Here, grasping angle ϕ is an angle from X-axis of the robot reference coordinates to the perpendicular line of (8). Finally, distance of the robot to the object L and grasping angle ϕ are shown in (10) and (11), respectively.

$$y = ax + b \tag{7}$$

$$y = -\frac{1}{a}x \tag{8}$$

$$\left(C_x, C_y\right) = \left(-\frac{ab}{a^2+1}, \frac{b}{a^2+1}\right) \tag{9}$$

$$L = \frac{b}{\sqrt{a^2+1}} \tag{10}$$

$$\phi = \tan^{-1}\left(-\frac{1}{a}\right) \tag{11}$$

C. Correction of Locomotion Direction

Correction of locomotion direction consists of correction of distance and angle, which refers to the values of L and ϕ. When grasping the front object, correction of the robot's distance was simply performed by walking in a backwards direction. For safety, the quantity of steps is calculated referring to the value of distance L. When grasping the right-side object, correction of distance involves trajectory generation of legs to take side-steps away from the object. However, in order to prevent the probability of collision when the robot performs a correction angle, if the grasping angle ϕ is $0<\phi\leq45°$ the robot will walk one step in a backward direction, before proceeding to take a side-step. If the grasping angle ϕ is $45°<\phi\leq90°$, the robot will immediately take a side-step away from the object. At this point, the side-step length S is defined from (12). Here, L_b is a safety distance between the robot and the object.

$$S = \left(L_b - L\right)\sin\phi \tag{12}$$

From (12), boundary conditions are fixed as (13) and (14). In these equations, α and β are minimum and maximum parameter values of step length of the humanoid robot legs during performance of a side-step.

$$S = \begin{cases} \alpha & \left(L_b - L \leq 0\right) \\ \left(L_b - L\right)\sin\phi & \left(L_b - L > 0\right) \end{cases} \tag{13}$$

$$S = \begin{cases} \beta & \left(\left(L_b - L\right)\sin\phi > \beta\right) \\ \left(L_b - L\right)\sin\phi & \left(\left(L_b - L\right)\sin\phi \leq \beta\right) \end{cases} \tag{14}$$

Correction of the robot's angle is performed by changing the robot's locomotion direction to $90°-\phi$, so that the robot's final orientation is parallel with the object's surface orientation. This correction motion is generated by rotating the hip-joint yaw to the desired angle while controlling the swing leg's end-point position. Figures 7 and 8 show a sequential photograph of the robot performing correction of position and angle after the self-localization process.

D. Obstacle Avoidance

Obstacle avoidance consists of three important tasks: checking the obstacle using left arm, rotating robot's orientation, and confirming obstacle using right arm. Basically, the tasks are performed after correcting the robot's distance, before proceeding to the correct angle. However, if no obstacle has been detected, the robot will continue correcting its angle. The left arm's range of motion while checking for obstacles is equal to the correction angle $90°-\phi$. Any objects detected are considered to be obstacles.
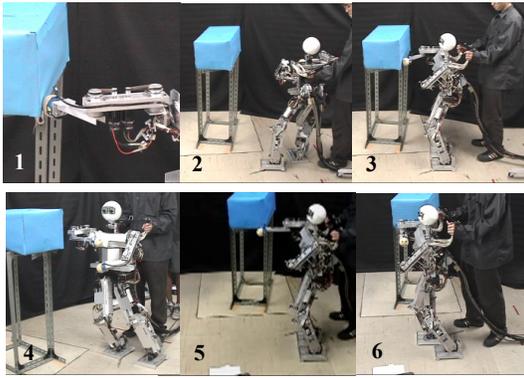
Fig. 9. Obstacle avoidance process in contact interaction-based navigation.

Figure 9 shows the obstacle avoidance tasks in the proposed navigation strategy. Once an obstacle has been detected during the process of checking for obstacles, the robot will rotate its orientation to face the obstacle in order to confirm the obstacle's position at a wider, more favorable angle, finally avoiding it. After the obstacle is detected and the robot orientation has changed to face the obstacle, it is necessary to confirm whether the obstacle still exists within the locomotion area. This process is performed by the robot's right arm, which searches for any obstacle in front of the robot within its reach. If the obstacle is detected within the search area, the robot will perform walking in a side-step direction. The robot's arm will repeat the process of confirming the obstacle's presence until the obstacle is no longer detected. Once this happens, the robot will walk forward and complete the process of avoiding the obstacle.

VI. MOTION PLANNING

Observation of human behavior during operation in a dark room shows that at first the human subject seems to search and identify the nearest object to recognize his position in the room. Inspired by this scenario, the humanoid robot starts the navigation process by searching for the nearest object to define self-localization so that it can recognize its position and orientation in the environment where the operation takes place. Continuously the robot generates suitable locomotion based on contact information; as described by the proposed algorithm explained in the previous section.

Lastly, the navigation of a walking robot requires accurate collision avoidance parameters. This is to ensure the safety of robot when performing locomotion in the navigation tasks. As mentioned in section IV, the robot trunk movement parameter r is one of the parameters which needs to be considered. The arm detection area which is equal to the length of arm L_t also needs to be considered as a parameter. The robot travel distance (step length and quantity of steps) in walking motions is controlled based on these parameter values. For forward and backward walking motion, travel distance must be less than the value of L_t. Whereas for the side-stepping motion and tangential walking during the correction process, the travel distance is fixed to be less than parameter value of $L_t + r$.
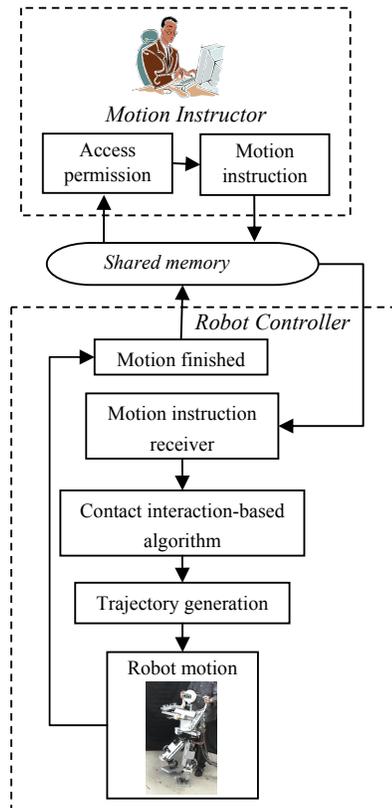
Fig. 10. Control system architecture in humanoid robot Bonten-Maru II.
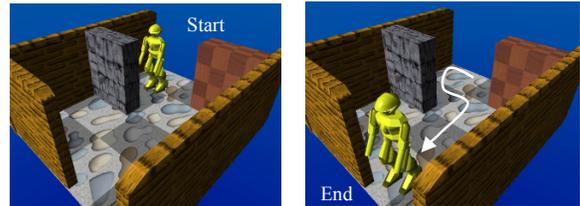
Fig. 11. Layout of the contact interaction-based navigation experiment.

VII. EXPERIMENT AND RESULT

An experiment is conducted using the prototype humanoid robot Bonten-Maru II to evaluate the proposed navigation strategy. The proposed navigation algorithm was installed in the robot control system as shown in Fig. 10. The experiment is conducted in a room where walls and obstacles are arranged as shown in Fig. 11. The robot vision sensors are not connected to the system, therefore the robot locomotion can only rely on contact interaction of the arms that are equipped with force sensors. A human operator acts as the motion instructor and controls the robot motions by sending instructions to the robot control system and received feedback of contact information from the robot controller module. The operator has prior knowledge of the room arrangement but does not know the exact starting position of the robot.

Figure 12 shows sequential photographs of actual robot locomotion during the experiment. At first the robot was searching for the nearest object using both arms. When the object was detected, the robot grasped the object surface to

Search front and right side	Search front and left side	Side-step to right	Search after side-step	Grasp object surface	Check obstacle to left
Correct angle left leg	Correct angle right leg	Search object	Check obstacle	Turn left	After turn left
Search front and right side	Search front and left side	Turn right	Turn right	After turn right	Walk forward
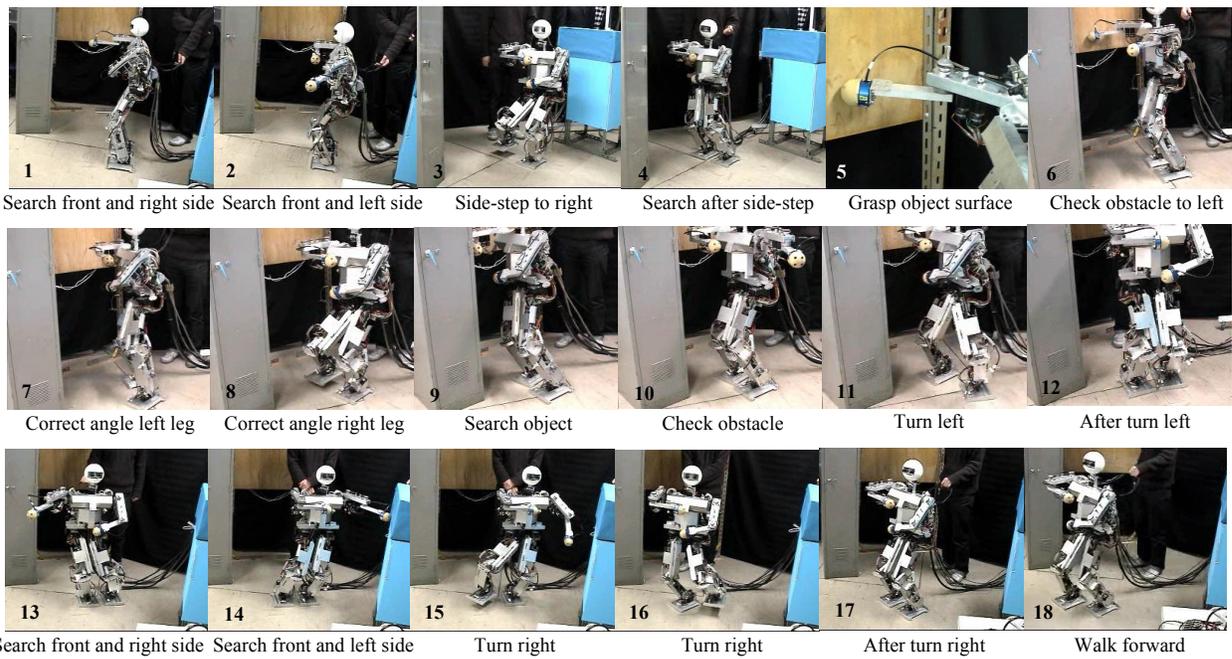
Fig. 12. Sequential photograph of humanoid robot locomotion in contact interaction-based navigation experiment.

define self-localization. Then the robot corrected its locomotion direction after checking for obstacle in the correction area. The robot continued its locomotion while touching and avoiding objects along its way. When it was necessary, the robot changed its direction by turning to right and left. Finally, the robot managed to complete the navigation tasks safely and reached the target end point.

VIII. CONCLUSION

We have presented the development of a contact interaction-based navigation strategy for a biped humanoid robot in which the arms are equipped with force sensors. We proposed a motion algorithm consisting of searching tasks, self-localization, correction of locomotion direction and obstacle avoidance. Priority was given to right-side direction to navigate robot locomotion in conjunction with strategies to avoid obstacles. The proposed algorithm was evaluated in an experiment with a prototype humanoid robot operating in a room with walls and obstacles. The experimental results revealed good performance of the robot locomotion in recognizing the environmental conditions and generating suitable locomotion to walk safely towards the target point. Finally, the proposed strategy was demonstrated to have good potential to support current visual-based navigation systems so that humanoids can further 'adapt' in real environment.

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