Performance evaluation of a behavior-based fuzzy controller for humanoid mobile robot

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Abstract— This paper presents the design and performance evaluation of a fuzzy controller for a humanoid mobile robot named VIEBOT. Using depth camera, the VIEBOT platform has the capability to explore surrounding environment to approach human target while avoiding collision with objects on its moving path. A behavior-based fuzzy controller for VIEBOT was designed to provide a mechanism for collaborating individual behaviors with different priorities. Various experiments were conducted in real office environment to validate and verify the design of this mechanism.

Keywords- humanoid robot; mobile robot; fuzzy control; behavior-based control;

I. INTRODUCTION

In the recent years, together with the advancements of computer vision, mobile humanoid robot can easily perceive the working environment [1, 2]. Moreover, by using hands and arms, it can perform a number of complex tasks similar to human activities [3, 4]. Most of humanoid robots have a torso, a head, two arms, observable ability, dexterity of hands, and locomotion ability. In comparison to legged locomotion, wheeled locomotion enables to consume energy more efficient and to control robot more simply, because of the capability of flexible navigation in either indoor/outdoor environment with obstacle avoidance [5, 6] and path planning [7, 8]. There are several studies combine the advantages of mobility and humanoid features (hands, arms) [9 - 12].

Applications of behavior-based control have been widely presented during the last few years, e.g. [13 - 15]. These applications provide good capabilities to design complex behaviors for robots. The key idea of behavior-based control is a hierarchical organization of parallel behaviors. This kind of organization permits parallel behaviors at the same stage to be stimulated concurrently. In addition, it is possible to make a complex behavior easier to design by separating such behavior to simpler behaviors. In comparison to the complex behavior, the simpler behaviors always stay at the lower stage of the hierarchical organization.

Fuzzy control was firstly introduced by Zadeh in 1965 [16]. The applications of fuzzy control permits robot to do flexible behaviors similar to the human thinking. A behavior-based fuzzy controller may support robot intelligent abilities to adapt to changing environments [17, 18].

In this study, we develop a new mobile humanoid robot platform named VIEBOT that has the capability of interacting with human and navigating in office environments. VIEBOT uses a depth camera as the main sensor for recognizing and tracking objects, human motions and gestures. Moreover, based on the generic system for behavior-based mobile robot in [19], a fuzzy controller is designed for VIEBOT to collaborate individual behaviors with different priorities that are changeable after encountering situations. This paper is organized as follows: the next section describe the design of the fuzzy controller. In the third section, the implementation of VIEBOT is presented along with the experiments to evaluate the performance of the fuzzy controller to drive VIEBOT safely to human target. The last section draws some concluding remarks and points out future directions.

II. FUZZY CONTROLLER DESIGN

In Fig. 1 is the principle diagram of the fuzzy behavior-based controller of VIEBOT. There are four functional modules named IP, TT, OA and AC.

![Figure 1. Behavior-based controller of VIEBOT](image-url)
Module IP (Image-based Perception) executes image processing to recognize objects from the input images, determines a human target to track, and measure object distances. The outputs of module IP are obstacle distance \(d_o\), target distance \(d_t\), and target angle \(\alpha_t\).

Module TT (Target Tracking) utilizes information concerning target distance \(d_t\), and target angle \(\alpha_t\) to reckon behaviors for tracking the human target. Module TT provides a velocity command \(v\) to control the robot track the target and the target angle \(\alpha\) to help the robot make a fuzzy-based collaboration later.

Module OA (Obstacle Avoidance) works out behaviors for avoiding obstacles on the road. Module OA supplies a velocity command \(v\) for driving the robot safely and the obstacle distance \(d_o\) to help the robot collaborate behaviors based on fuzzy logic rules.

Module AC (Action Collaborator) carries out a fuzzy-based coordination between the functional behaviors \(v\) and \(v\) to figure out a final velocity command \(v\) to operate the robot tracking target without any collision.

### A. Module IP

The operation principle of module IP is shown in Fig. 2. The image and depth streams taken from a depth camera (which is a MS Kinect v2) are processed in a computer Intel NUC. The image processing concerns image enhancement, color processing, segmentation, representation, and object recognition.

![Image processing](image)

**Figure 2.** Operation principle of module IP

Stemming from object recognition, the computer extracts object information concerning target angle \(\{\alpha_t \mid 90 \leq \alpha_t \leq 90\}\), target distance \(d_t = \{d_1, d_2, d_3\}\), and obstacle distance \(d_o = \{d_{front}, d_{left}, d_{right}\}\).

### B. Module TT

The structure of module TT is illustrated in Fig. 3 with two main sub-modules TTB and TTC.

**Figure 3.** Structure of module TT

Sub-module TTB (Target - Tracking Behaviors) computes primitive behaviors for tracking a desired target such as target-directing behavior and target-approaching behavior. The outputs of sub-module TT are velocities \(v_{DR}\) for target-directing behavior and \(v_{AP}\) for target-approaching behavior.

The velocity of target-directing behavior \(v_{DR}\) is depended on the target angle as follows:

\[
v_{DR} = f_1(\alpha_t)
\]

where \(f_1\) is a function of target angle \(\alpha_t\) defined by the user.

**Figure 4.** Membership functions of \(\alpha_t\) and \(d_t\)

The velocity of target-approaching behavior \(v_{AP}\) is depended on the target distance by the following equation:

\[
v_{AP} = f_2(d_t)
\]

where \(f_2\) is a function of target distance \(d_t\) given by the user.

**Figure 5.** Fuzzy relationship between \(\alpha_t\) and \(d_t\)

Sub-module TTC (Target - Tracking Coordinator) executes a fuzzy-based coordination between the target tracking behaviors.

The coordination between the target tracking behaviors \(v_{DR}\) and \(v_{AP}\) is calculated by the following expression:

\[
v_t = k_o v_{DR} + (1 - k_o) v_{AP}
\]

where
+ \( v_c \) is the output velocity for tracking the desired target;
+ \( k_d \) is a factor depended on \( \alpha_t \) by fuzzy logic rules:

- \( \mu \rightarrow \) large THEN \( k_d \) big
- \( \mu \rightarrow \) middle THEN \( k_d \) mid
- \( \mu \rightarrow \) small THEN \( k_d \) small
- \( \mu \rightarrow \) zero THEN \( k_d \) null.

The membership functions of \( \mu \) and \( k_d \) are illustrated in Fig. 4. The fuzzy relationship between \( \mu \) and \( k_d \) are shown in Fig. 5. The output of sub-module TTC is velocity \( v_T \) which is fed to module AC.

C. Module OA

The organization of module OA is displayed in Fig. 6 with two main sub-modules OAB and OAC.

Sub-module OAB (Obstacle Avoidance Behaviors) reckons primitive behaviors to prevent VIEBOT from collision during travelling. The outputs of sub-module OAB are three velocities \( v_{GF} \), \( v_{GB} \), and \( v_{GA} \) for three primal behaviors including going-forward, going-backward, and going-away, respectively.

![Figure 6. Organization of module OA](image)

The velocities \( v_{GF} \) and \( v_{GB} \) control motion of VIEBOT in two opposite directions, forwards and backwards, respectively. Both of them are depended on obstacle distances as the following equations:

\[
\begin{align*}
v_{GF} &= f_1(\sigma) = \min (d_o) \\
v_{GB} &= f_1(\varepsilon) = \text{constant}
\end{align*}
\]

where:
+ \( f_1 \) and \( f_\varepsilon \) are functions of obstacle distance defined by the user;
+ \( \sigma \) is a minimum distance of obstacles considered as the nearest obstacle.
+ \( \varepsilon \) is an emergency distance defined by the user.

The velocity of going-away behavior \( v_{GA} \) drives robot away from dangerous area by changing direction. Mathematically, it is depended on the difference between object distances on the left and right directions by the following expression:

\[
v_{GA} = f_4(\Delta) = d_{\text{left}} - d_{\text{right}}
\]

where \( f_4 \) is a function defined by the user. Sub-module OAC (Obstacle – Avoiding Coordinator) carries out a fuzzy-based collaboration among three behaviors \( v_{GF} \), \( v_{GB} \), and \( v_{GA} \) to give out a coordinated velocity \( v_c \). The formulation of the collaboration is:

\[
v_c = k_f v_{GF} + k_g v_{GB} + k_\lambda v_{GA}
\]

where \( k_f \), \( k_g \), and \( k_\lambda \) are weight factors depended on \( \sigma \) defined by the user.

![Figure 7. Membership function of \( s \)](image)

![Figure 8. Fuzzy relationships between of \( k_f \), \( k_g \), \( k_\lambda \) and \( s \)](image)

The membership function of \( s \) is shown in Fig. 7. The fuzzy relationships between \( k_f \), \( k_g \), \( k_\lambda \) and \( s \) are illustrated from Fig. 8 from left to right, respectively.

D. Module AC

![Figure 9. Structure of module AC](image)
Module AC performs a fuzzy-based coordinator between two inputs concerning velocities of target-tracking behavior and obstacle-avoiding behavior based on obstacle distance and target angle. The structure of module AC is shown in Fig. 9.

The result of the fuzzy-based functional coordination is a velocity \( v \), computed by the following equation:

\[
v = k_t v_t + k_c v_c
\]

(8)

where \( k_t \) and \( k_c \) are functional factors changed after the nearest obstacle distance \( r = \min(d_c) \) and the absolute value of target angle \( j = \vert j \vert \) by the following fuzzy logic rules:

- \( r \) danger THEN \( k_t \) null AND \( k_c \) big
- \( r \) near AND \( j \) small THEN \( k_t \) small AND \( k_c \) big
- \( r \) near AND \( j \) mid THEN \( k_t \) mid AND \( k_c \) big
- \( r \) near AND \( j \) big THEN \( k_t \) big AND \( k_c \) big
- \( r \) mid AND \( j \) small THEN \( k_t \) mid AND \( k_c \) mid
- \( r \) mid AND \( j \) mid THEN \( k_t \) big AND \( k_c \) mid
- \( r \) mid AND \( j \) big THEN \( k_t \) big AND \( k_c \) small
- \( r \) far THEN \( k_t \) big AND \( k_c \) small.

The fuzzy relationships of target factor \( k_t \) and collision factor \( k_c \) with \( r \) and \( j \) are illustrated in Fig. 10 and Fig. 11, respectively. It is noticed in Fig.10 that target factor \( k_t \) is directly proportional to the minimum object distance \( r \) and to the target angle \( j \). Otherwise, in Fig. 11, collision factor \( k_c \) is inversely proportional to the minimum object distance \( r \) and to the target angle \( j \).

The output of module AC is a velocity \( v \) used as a robot locomotion command to control the robot to navigate and track a target in a safe way. This velocity is changed after not only \( v \), but also \( k_t \) and \( k_c \) in different situations of the working environment.

III. IMPLEMENTATION

A. VIEBOT

VIEBOT is a multi-purposed humanoid mobile robot platform developed by Vietnam Research Institute of Electronics, Informatics and Automation (http://vielena.com). The 3D design of VIEBOT is illustrated on the left side in Fig. 12 and the real appearance of a beta version is showed on the right side in Fig. 12.

VIEBOT is shaped similar to a woman with the height of 160 cm and weight of approximately 50KG. It is equipped with depth camera (a MS Kinect v2 with HD resolution), sonar sensors, touch screen and an Intel NUC core i5 3GHz as the main CPU.

VIEBOT travels on a three-wheel platform including two active wheels and one passive one. The motion control signals of the active wheels are transmitted via 2 motors. The speed \( v \) of the motors is controlled by the locomotion command.

The behavior-based controller of VIEBOT is structured as the illustration in Fig. 1. Based on perception of the kinect camera, VIEBOT can detect a desired target and measure object distances for locomotion control.

B. Testbed

To automatically record the trajectories of VIEBOT in the experiments, a simulated map of the experimental environment is created by the software POV-Ray (Persistence of Vision Ray-Tracer). The simulated map is displayed in Fig. 13.
In the office environment there are some rooms, doors, corridors, office furniture such as chairs and tables. The office is simulated as a map on the computer. In the simulated map, a trajectory of robot is automatically drawn by a colorful line. For easy debugging of Robot movement, the software automatically change color along the line.

C. Experiment objectives

The experiments are classified in 4 groups E1 to E4:
- Group E1 tests the ability to deal with emergency situations where an obstacle is too close in front of VIEBOT.
- Group E2 tests the ability to deal with obstacles randomly arranged along the travelling road.
- Group E3 tests the ability to recognize a person, track him and avoid obstacles on the road.
- Group E4 tests the scenario of VIEBOT operating in multiple-human environment.

D. Experiment results

In experiments E1, when an obstacle was placed closer than the emergency distance $\varepsilon$, VIEBOT stopped going forward and gave the highest priority for going back behavior until it stayed far enough from the obstacle. This demonstrates that $k_y < k_c$ and $v_{GB}$ occupies the highest priority.

In experiments E2, VIEBOT wandered along the corridors, where some obstacles randomly arranged, see a situation displayed in Fig. 14. The results show that VIEBOT can avoid all of the obstacles. They can be explained that because no person was detected, VIEBOT gave the obstacle avoiding behavior a higher priority to deal with the obstacles. These means that $k_y < k_c$; $v_{GB}$ and $v_{GA}$ occupy the highest priorities.

In experiments E3, VIEBOT traveled around the office from one room through a corridor to another room. The results were that VIEBOT succeeded in recognizing a person (a person wearing a black pullover) and assigning him to a target. After recognizing him, VIEBOT immediately tracked and followed him along the corridor and navigate into a room. During this tracking process, VIEBOT also successfully avoided the obstacles along the path. One trajectory of E3 is automatically recorded on the simulated map as the right illustration in Fig. 15. These results prove that both $k_y$ and $k_c$ were stimulated in the situations.

In experiments E4, VIEBOT moved around the office in the other direction and recognize a second person (who is wearing a white t-shirt). The movements of VIEBOT in E4 were automatically recorded on the simulated map as shown on the right photo in Fig. 16. Similar to E3, during tracking the human target, VIEBOT successfully avoided obstacles randomly arranged along the corridor. In this experiment, not only the number of human is doubled but also the density of obstacles is higher than that in the E3. These results certify that once again, both $k_y$ and $k_c$ were stimulated in such the situations.

The experimental results showed that the behavior-based fuzzy control successfully and safely drive VIEBOT in a complex environment while tracking a human target.
IV. CONCLUSION

This paper presents a design and performance evaluation of a behavior-based fuzzy controller for humanoid mobile robot VIEBOT. Utilizing high resolution depth camera and sophisticated fuzzy logic controller, VIEBOT can detect a human target to track and approach him while avoiding collision with random objects on its moving path. The fuzzy algorithm allows the robot to move at optimized speed that minimize the risk of collision while reduce navigation time to the target. Various experiments in real-world indoor office environment with human and objects have proven the efficient of the design. In the future, the team will improve the algorithm to deal with more complex environments linked with requirements from various applications of this robot platform such as advertisement, service, hospital and manufacturing environment.

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The preferred spelling of the word “acknowledgment” in America is without an “e” after the “g”. Avoid the stilted expression, “One of us (R. B. G.) thanks . . . .” Instead, try “R. B. G. thanks”. Put sponsor acknowledgments in the unnumbered footnote on the first page.

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