

Human Friendly Autonomous Robot using Dempster-Shafer Sensor Fusion and Velocity Potential Field Control

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Abstract— In this paper, a human friendly autonomous robot, was presented. Navigation of this robot applies sensor fusion technique based on Dempster-Shafer method and velocity potential field. The controller of the autonomous mobile robot is designed to lead the robot toward the goal while avoiding collisions in complex environments and maintain human safety as a first priority. The approach is based on Dempster-Shafer sensor fusion of signals from sonar and passive infrared sensors to allow the robot to identify human presence. A velocity potential field robot controller is formulated for the case of avoiding collisions while giving higher priority to collision avoidance with humans as opposed of objects. Simulations and experiments illustrate the performance of the approach in extreme situations.

Keywords- human friendly robots; Dempster-Shafer evidence theory; sensor fusion; human safety.

I. INTRODUCTION

Recently, with rise of the cost of labor, robots play more important roles than before. To become more widely applied in the real world, it is necessary that the mobile robots have much more artificial intelligence to work in more complex environments, which might include humans or vehicles with unknown and unpredictable motions, such as factory or home environments. To achieve this goal, the robot has to be able to identify and distinguish the obstacles, and the human and avoid collisions with both of them. Furthermore, the robot should always put human safety as its first consideration.

In this paper, a sensor fusion approach based on Dempster-Shafer evidence theory is combined with velocity potential field approach used for robot control. The justification of this choice is the ability of Dempster-Shafer evidence theory to include supporting evidence, refuting evidence and an uncertainty interval, that permit a suitable use of expert knowledge regarding autonomous robots navigation issues. The detection area of the robot is subdivided into several zones. The sensor fusion approach is employed to fuse both uncertain observations of sonar sensors and passive infrared sensors and to estimate the probability of being occupied by a human in each zone [1] [2]. Then, a human friendly mobile robot navigation approach is used for robot motion control. The controller is

based on the velocity potential field method (VPF), which is used to lead the robot moving to the goal avoiding the obstacles [3]. For the novel controller, in this case an improvement of the VPF allows the robot to avoid the human a first priority and only afterwards the obstacles. This novel VPF approach was not applied before for robot collision avoidance. Dempster-Shafer evidence theory permits to fuse outputs from various sensors and then provide the VPF controller with the required distances between the robot, the obstacles and the goal. The paper focuses on the novel results presented in the thesis [14].

The paper presents in Section 2 the Dempster-Shafer evidence theory used for sensor fusion. Section 3 focuses on the model used for the calculation of the avoidance distance to obstacles. Section 4 presents velocity potential field approach for robot navigation in the presence of humans. Simulation results are the topic of section 5, while experimental results are presented in Section 6, followed by conclusions in Section 7.

II. SENSOR FUSION METHOD BASED ON DEMPSTER-SHAFFER EVIDENCE THEORY

In this paper, two types of sensors are used to help the robot sense the environment. The first one is the Passive Infrared Sensor (PIR sensor), which senses the heat emitted by humans. PIR sensor is, however, not sufficiently accurate. Performing hundreds of experiments, in at about 10 % of the experiments the human sensor did not work well. Besides, PIR sensor might identify warm air generated by a heat source as coming from a human. The second type of sensor is the ultrasonic sensor. It emits high frequency sound waves to the objects and then receives them to determine how far they are. Since human is the first priority of the robot, information which is collected by different kinds of sensors is combined to identify human with a higher probability [4]-[9].

Dempster-Shafer evidential theory (D-S theory) was chosen to support the probability calculation given its ability when the sensors contributing information cannot associate a 100 % probability to their output decisions. The algorithm captures and combines whatever certainty exists in the

object-discrimination capability of the sensors. Knowledge from multiple sensors about events (called propositions) is combined using D-S theory to find the intersection or conjunction of the propositions and their associated probabilities [4], using

$$m(C_k) = \frac{\sum_{A_i \cap B_j = C_k; C_k \neq \emptyset} m(A_i)m(B_j)}{1 - \sum_{A_i \cap B_j = \emptyset} m(A_i)m(B_j)} \quad (1)$$

where A_i and B_j are the focal elements of m_A and m_B , respectively. m_A and m_B are the Basic Probabilities Assignments (BPA) which are combined while C_k are the focal elements of the combined BPA [12].

The frame of discernments is in this case a set of cells in the occupancy grids as shown in Figure 1. The eight grids are able to cover the human sensors detection area.

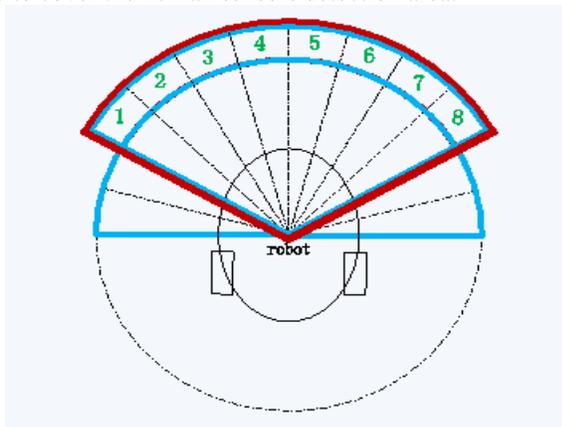


Figure 1. Human Sensors Detection Area

Both ultrasonic sensors and PIR sensors keep watching and each sensor contributes by assigning its BPA over its own frame of discernments [10] [11].

The D-S theory is used to combine two focal elements BPAs.

Sensor fusion is an iterative process with a time step chosen of 0.05s, described as follows:

1. Read the ultrasonic sensor outputs looking for the presence of a human. (assign the BPAs to each grid)
2. Read the human sensors outputs.(assign the BPAs to each grid)
3. Combine the final results of both kinds of sensors using D-S theory after one time step.
4. Calculate the probability (the combined BPAs) that quantifies how probable the grid is to be occupied by a human.
5. Compare the probability value with the setting value and make the decision whether there is a human in the grid and then generate a corresponding response.
6. Initialize the BPA of the occupied grid to zero to restart

the all progress.

7. Repeat from step one again until the mission is completed.

III. CALCULATION OF THE AVOIDING DISTANCE

The robot, the human zone and obstacle zone, shown in Figure 2, were built around the robot to avoid collision even in the worst case when the robot has the least amount of time to avoid a head-on collision. We denote the human zone from Figure 2 as A_0 the obstacle zone as A_1 and the work area excluding A_0 and A_1 as A . The shapes of the zones were designed based on the positions of the sensors.

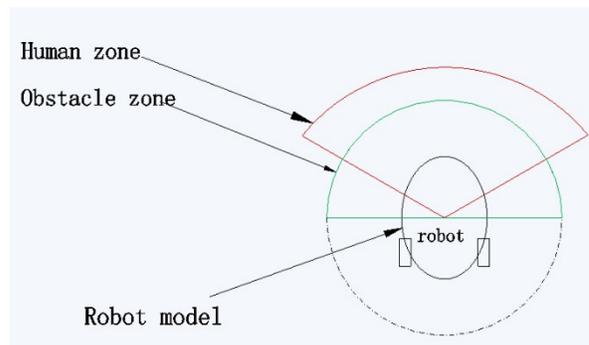


Figure 2. The Human Zone and the Obstacle Zone

The human zone was designed for human avoidance. In the worst human avoidance case, the human and the robot were moving toward each other.

Once the robot detected the human in its human zone, it turns into a different direction, from the original direction toward the goal, to avoid the collision. Given the human size and velocity of the human and the robot

$$r_h = 0.4m \quad (2)$$

the calculation is based on

$$\bar{\delta}_{mry} = \bar{V}_{mr} \times (\Delta t_1 - t_a) + \int_{t_a}^{\Delta t_1} a_{mry} dt \geq r + \rho_h \quad (3)$$

$$\bar{V}_{mr} \times (\Delta t_1 - t_a) + \frac{1}{2} a_{mry} t_a^2 = \delta_{mry} \geq r + \rho_h \quad (4)$$

where \bar{V}_{mr} is the maximum velocity of the robot, t_a is the time that robot needs to accelerate from zero velocity to \bar{V}_{mr} in Y-direction, $\bar{\delta}_{mry}$ is the distance that the robot is moving in Y-direction, r is the radius of the robot, a_{mry} is the robot

acceleration magnitude in Y-direction, Δt_1 is the total time of the avoidance and r_h is the radius of human active area. Finally, the radius of the human zone r_0 should satisfy the constraint

$$r_0 \geq \bar{\delta}_{hx} + \bar{\delta}_{mrx1} \quad (5)$$

where $\bar{\delta}_{hx}$ and $\bar{\delta}_{mrx1}$ is the human and robot moving distance in X-direction, respectively. Based on the above model, calculation for the worst case, gives the radius of the human zone of 30cm.

IV. VELOCITY POTENTIAL FIELD METHOD WITH THE CONSIDERATION OF HUMAN PRESENCE

In this paper, the velocity potential field method [3], obtained from velocity potentials defined in hydrodynamics, is modified for planning a path which avoids collisions with the human and the obstacles, such that, during the avoidance, the robot will avoid the human before it starts to avoid the obstacles. The robot is guided by its velocity commands which are given by its navigation controller (Figure 3).

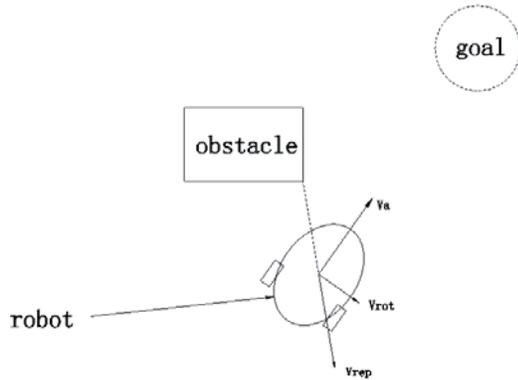


Figure 3. The Attractive, Rotation and Repulsive Velocity Commands

The distance between robot and goal d_{goal} is

$$d_{goal} = \sqrt{(yG - y)^2 + (xG - x)^2} \quad (6)$$

where (xG, yG) refers to the goal and (x, y) to the center and robot.

The goal radius is

$$g_{rad} = 0.4m$$

VPF approach, presented in detail in [3], results in velocity commands for the robot controller.

The attractive velocity function is defined as [3]

$$V_a = 2 \times \bar{V}_{mr} \times \left(1 - \ell^{-\frac{d_{goal}}{g_{rad}}}\right) \quad (7)$$

where \bar{V}_{mr} is the maximum velocity of robot.

The repulsive velocity function is defined as [3]

$$V_{rep} = 0.5 \times \frac{1}{d_{obs}} \times \ell^{-\frac{d_{obs}}{obs_{rad}}} \quad (8)$$

where d_{obs} is the distance between the obstacle and the robot which is obtained by the sensors.

Here, we also created a repulsive velocity function for the human, which has a larger gain than the repulsive velocity function for obstacle

$$V_{rephuman} = 0.7 \times \frac{1}{d_{obs}} \times \ell^{-\frac{d_{obs}}{obs_{rad}}} \quad (9)$$

Both $\frac{1}{d_{obs}}$ and $\ell^{-\frac{d_{obs}}{obs_{rad}}}$ in the equation cause a sustained

increase of the repulsive velocity if the robot keeps approaching the obstacles or human, which means that the closer the obstacle or human is, the larger is the repulsive velocity.

The rotation velocity function is defined as [4]

$$V_{rot} = 0.5 \times \frac{1}{d_{obs}} \times \ell^{-\frac{d_{obs}}{obs_{rad}}} \quad (10)$$

where d_{obs} is the distance between obstacle and robot which is obtained by the sensors.

The resultant velocity command is given by

$$V_{sum} = \begin{cases} V_a, P_r \in A \\ V_a + V_{reph} + V_{roth} & P_r \in A, P_h \in A_0 \\ V_a + V_{reph} + V_{roth} & P_r \in A, P_h \in A_0, P_h \in A_1 \\ V_a + V_{rep} + V_{rot} & P_r \in A, P_{obs} \in A_1 \end{cases} \quad (11)$$

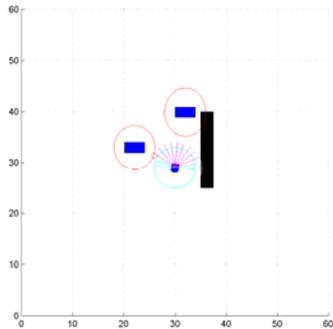
where V_a , V_{rep} , and V_{rot} , are the attractive, repulsive and rotation velocity commands, respectively. The V_{reph} , and V_{roth} are velocity commands regarding a human. A is the whole map area while A_0 and A_1 represent the human zone and obstacle zone.

V. SIMULATION RESULTS FOR HUMAN FRIENDLY ROBOT

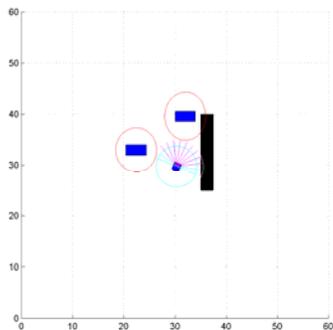
In order to test if the robot is able to avoid collisions as expected, simulations were carried out using MATLAB™. Figure 4 presents the results of the simulation with the following symbols:

- The blue rectangle with the red circle: the human
- The black rectangle: the obstacle
- The blue polygon with light blue circle: the robot

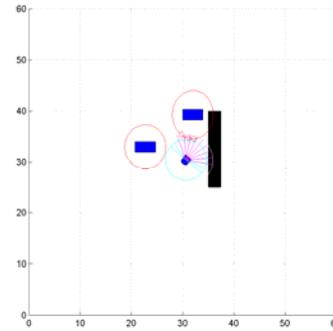
In these simulations, the robot did not know it will face a dangerous situation. The aim of creating such an extreme situation is to test if the robot controller has the ability to avoid the human and the obstacle while it still has time and space.



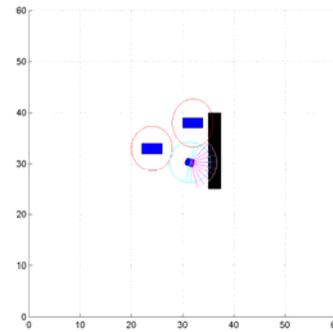
(a)



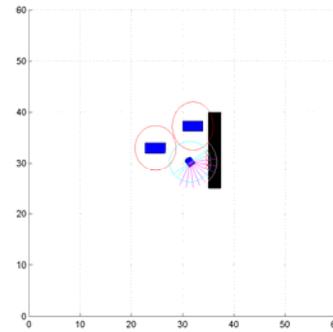
(b)



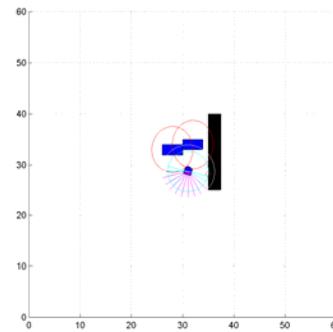
(c)



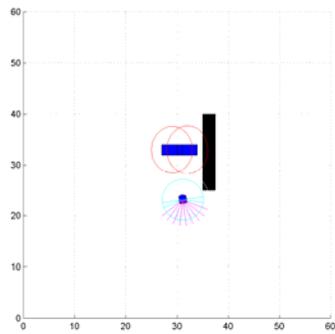
(d)



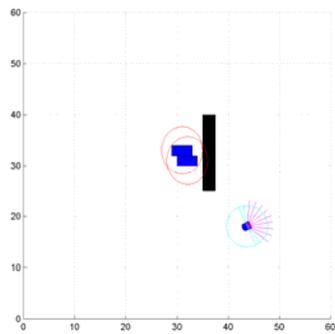
(e)



(f)



(g)



(h)

Figure 4. Higher Human Priority (Two Humans and One Obstacle)

As shown in Figure 4, the robot turned around and ran away from the two human and, afterwards avoided the obstacle moving in a direction where there is no danger. This illustrated that the proposed VPF based controller permits to avoid fixed obstacles and avoid humans and arrive to the designated goal.

VI. EXPERIMENTAL RESULTS

Experiments were carried out for the same scenario as in simulations, in which the robot suddenly faces the moving human and obstacles at the same time and, during the avoidance, the robot should detour human and obstacles with different priorities, such that the human always has a higher priority in avoiding collision than obstacles.

For this scenario, two humans kept approaching the robot located in front and left side and the wall was in its right side. The purpose to design this situation is to test if the robot is able to avoid humans first (even has a risk to collide with an obstacle) and only afterwards to start avoiding the obstacles. As we can see from the Figure 5, the robot avoided the two humans first even while moving in the direction of the wall. Then, the robot avoided the wall and ran away from the danger of collision. It can be noted that the simulation results from Figure 4 (a)-(f) correspond

to the snapshots of experimental results from Figure 5 (a)-(f). Experimental results confirmed that the proposed combination of Dempster-Shafer sensor fusion with velocity potential field based controller successfully avoided fixed obstacles and humans in moving towards the designated goal.



(a)



(b)



(c)



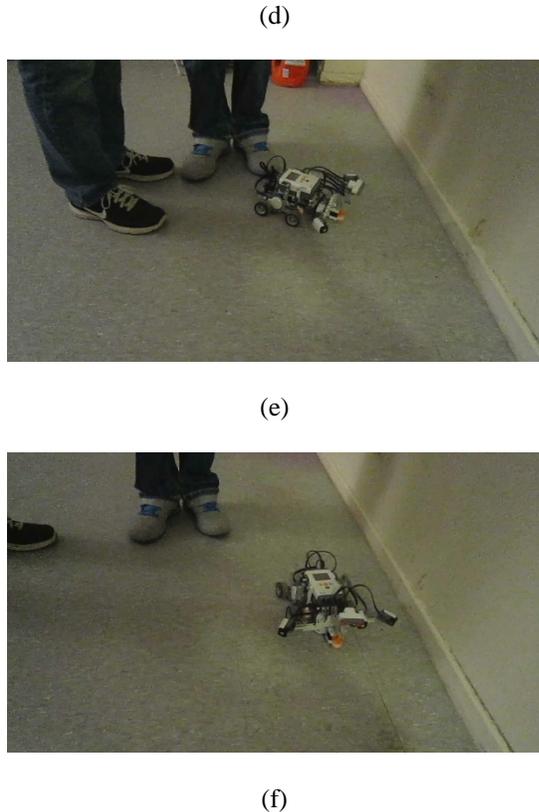


Figure 5 Two Human and One Obstacle Avoidance

VII. CONCLUSIONS

The paper presents a novel approach to robot-human collision avoidance using Dempster-Shafer method based on evidence theory. This methodology allows to integrate signals from multiple sensors. This supplies more reliable distance estimation to a velocity potential field controller.

The results presented in this paper show that the new human friendly mobile robot navigation controller based on Dempster-Shafer sensor fusion is able to lead the robot, avoid collisions with the obstacles and humans while always maintaining human safety as its first priority.

In the extreme case, when the robot does not have enough room to avoid the collision with the human and an obstacle, it chooses to protect the human even if in the process it might collide with an obstacle.

In the work presented in this paper, the robot has only one infrared sensor to sense the human. Although the sonar sensor helps the infrared sensor it cannot distinguish human

on its own. This method is good enough for human detection, but it cannot ensure complete security for the human. In the future, another sensor based on infrared camera will have to be added to the robot so that human movements can be further recorded by the robot through processing pictures captured by the infrared camera and thus the human safety can be further improved.

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