Cooperative Path Planning for a Heterogeneous Robotic System composed of a Humanoid Robot and a Wheel Robot

ANDRE M. SANTANA*, ADELARDO A. D. MEDEIROS*
Departement of Computer Engineering and Automation (DCA)
Federal University of Rio Grande do Norte (UFRN)
Natal - RN - Brazil
Emails: [andremacedo,adelardo]@dca.ufrn.br

***Abstract*— This study presents a path planning strategy for a robotic system, subject to visibility restrictions, composed of a humanoid robot and a wheel robot. The planner calculates a cooperative pathway, assuming a known map a priori, considering that the humanoid robot is identified by a mark placed inside its front portion and all information processing is executed in the mobile robot. Experimental results validated the proposed idea.**

I. INTRODUCTION

To decide which path to follow to perform a task one needs some form of planning. Decisions based on the criterion of optimality (shortest path, safest path, etc.) are dealt with in robotics as a path planning problem.

In mobile robotics, path planning refers mainly to the ability that a mobile robot has to choose, among several possibilities, the path which, according to optimality criteria, it intends to follow.

In order to be executed, the planning phase needs an initial and final robot configuration defined in a same reference system. In addition, one normally assumes the knowledge of a map based on that which will assess the options, the current position toward which it is moving and existing obstacles. Using this information, the planner must be able to generate a geometric curve that leads the robot safely between the two configurations, avoiding obstacles when they appear.

Choset et al. (2005) [1] and Lavalle (2006) [2] consider that current path planning approaches can be divided into three groups: methods that use roadmaps, methods that use potential fields and cell decomposition methods.

Pimenta et al. (2004) [3] proposed path planning for robots that uses finite element methods. With these methods, the working space of the robot is translated into boundary conditions for Laplace's equation. Laplace's equation is solved using finite element methods that result in a potential value for each knot in the mesh. From these potentials one calculates gradient values for each element and uses them as a potential field to navigate the robots. Adôrno et al. (2005) [4] used probabilistic roadmaps as a trajectory generating strategy using as interpolator based on Bezier's curves.

This work presents a path planner for a robotic system composed of a humanoid robot and a wheel robot subject to visibility restrictions. Owing to the nonholonomic and visibility restrictions of the two robots, this problem resembles those of the mobile robot (robotic coordination, leader follow, robot with a trailer, etc) involving cooperative path planning. Accordingly, these problems were investigated in the literature.

Em Ghabchelo et al. (2005) [5] and Carelli et al. (2006) [6] propose a centralized cooperation strategy based on an omnidirectional vision system, where the leader is responsible for generating the path and coordinating the tasks. In Fujimori et al. (2005) [7], the follow- the -leader task is performed using an artificial vision system with a perspective camera, with which the trailing robot receives information about position and direction from the leading robot.Han et al. (2004) [8] analyzed trajectories when the tow-robot system follows a number of types representative of the paths and proposed the "overall-size concept", to be used when representing obstacles in the working space. Based on this concept, a method that models the environment is proposed.

Lamiraux et al. (2005) [9] present an agreement between the Airbus company and the French government for the overland transport of the basic components of the Airbus 380 (wings, the rear and central portion, front fuselage and the horizontal tail plane) using two types of tow-trucks that were designed for transporting the parts. The truck movement planning is based on robotic navigation techniques. The strategy used consists of generating, a priori, a trajectory pattern and then "deforming it", using potential fields, to incorporate the nonholonomic restrictions of the truck movements and ensure that the path is the safest possible.

A detailed description of the problem in question will be presented below, as well as the solution proposed, the results obtained and final comments and perspectives about this work.

II. PROBLEM DESCRIPTION

The problem approached in this study consists of planning a cooperative path, assuming a known map a priori, for a heterogeneous robotic system composed of a non-instrumented humanoid robot and a mobile wheel robot. The humanoid robot is identified by a mark in its front portion and all information processing is executed in the mobile robot, which contains a laptop computer attached to its structure (Figure 1).

Fig. 1. Robotic System.

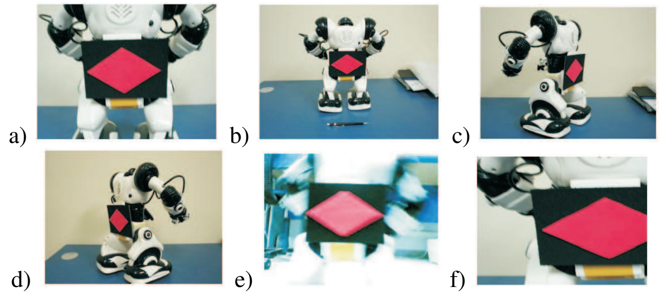

Fig. 2. Humanoid Images.

The movement of the wheel robot depends entirely on the movement of the humanoid robot, since the former must follow the latter and always ensure a good image. The main problem with positioning the robot on wheels is not guaranteeing that it reaches a final desired position, but rather that it always stay behind the humanoid and maintain good vision.

Owing to the need of the wheel robot to maintain the humanoid's good vision while always positioning itself behind it, three visibility restrictions of the mark must be taken into account during path planning:

- distance (maximum and minimum) between the robots;
- the relative angle between them;
- viewing angle of the camera.

The required distance is important because it is directly related to the size of the mark in the image. The farther apart the robots are, the smaller the size of the image will be, making its detection difficult. When the robots are very close to each other, problems related to abrupt movements on the part of the humanoid may influence the detection of the mark.

In regard to the angle between the robots, it can be observed that the increase in its module creates problems in identifying the mark, since the projection of the mark on the 2D plane becomes increasingly smaller.

With respect to the camera viewing angle, for an effective identification of the mark, it must appear in its entirety in the image captured by the camera.

To illustrate the aforementioned problems, Figure 2 presents several humanoid images.

- (a): humanoid image captured from a distance of 20*cm*;
- (b): humanoid image captured from a distance of 40*cm*;
- (c): humanoid image rotated 45^o counter-clockwise direction;
- (d): humanoid image rotated 45^o clockwise direction;
- (e): image of the humanoid in movement;
- (f): humanoid image from 10*cm*, where the mark appears only partially in the image;

Traditional planning techniques calculate paths without considering the nonholonomic restrictions of the robots.

Normally, the path is calculated and later it is adapted to incorporate these restrictions.

The application of these techniques to the robotic system used in this work becomes unfeasible because the system is composed of two heterogeneous robots.

The proposal of a planner that calculates the path, respecting the nonholonomic restrictions of the two robots and the visibility restrictions present in the system, will be discussed in the next section.

III. SYSTEM PROPOSED

To avoid the problems cited in the previous section, the planner developed considers the system (humanoid and wheel robot) as a viable structure subject to vision restrictions. Figure 3 shows how the system was modeled and presents the restrictions imposed.

As previously mentioned, the distance restriction refers to the maximum and minimum distances. The field of vision restriction refers to the problem of the camera's viewing angle and the visibility restriction to the problem of the relative angle between the robots.

The planner developed sets up a graph where each knot has, among other information, the position of the humanoid (x_H, y_H, θ_H) and the position of the wheel robot (x_R, y_R, θ_R). The graph expansion phase is done considering that the set of robot movements is a set of eight elements (Figure 4).

Consider as legend:

- ΔL_H: step of linear motion of humanoid;
- $\Delta\theta_H$: step of angular motion of humanoid;
- ΔL_R: step of linear motion of wheel robot;
- $\Delta\theta_R$: step of angular motion of wheel robot;

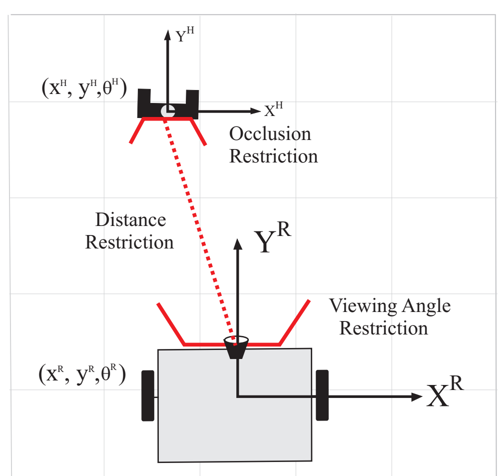

Fig. 3. Restrictions of the System.

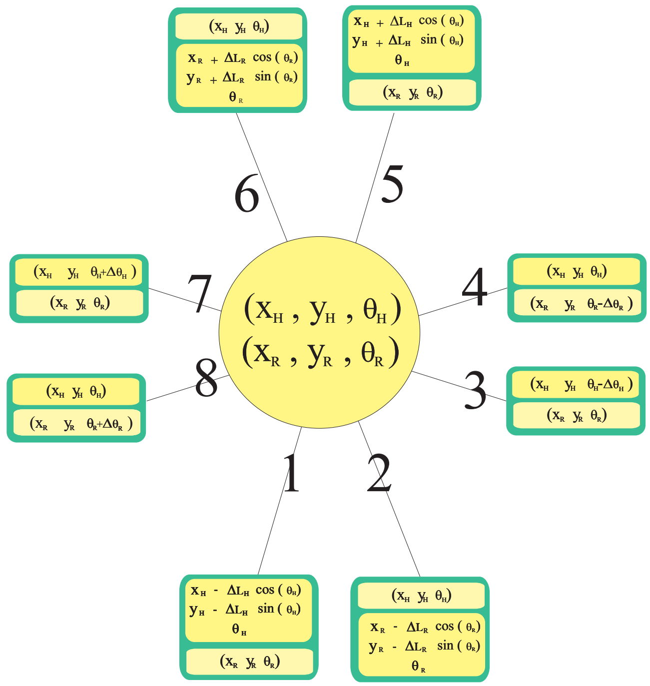

Fig. 4. Graph.

- **(1)**: moving back the humanoid;
- **(2)**: moving back the wheel robot;
- **(3)**: movement of spin of humanoid (clockwise);
- **(4)**: movement of spin of wheel robot (clockwise);
- **(5)**: moving forward the humanoid;
- **(6)**: moving forward the wheel robot;
- **(7)**: movement of spin of humanoid (counter-clockwise);
- **(8)**: movement of spin of wheel robot (counter-clockwise);

The vision restrictions of the system were incorporated into the validation stage of the new knot generated. In this stage the test that assesses on the map if the new knot is an obstacle is traditionally performed. If so, this knot is not added to the graph. In the planner proposed, the validation of the knot is done by testing if the position of the humanoid or of the weel robot is within an obstacle and if it obeys the following conditions of equations (1), (2), (3) and (4).

If the expanded knot does not obey any of the conditions, it is considered a virtual obstacle and is not added to the graph.

$$|\alpha_{rel} - \theta_H| < \alpha_{max}^{cam} \tag{1}$$

$$|\alpha_{rel} - \theta_H| < \alpha_{max}^{mar} \tag{2}$$

$$\sqrt{(x_H - x_R)^2 + (y_H - y_R)^2} > D_{min} \tag{3}$$

$$\sqrt{(x_H - x_R)^2 + (y_H - y_R)^2} < D_{max} \tag{4}$$

where,

- D_{max}: maximum distance between the robots;
- D_{min}: minimum distance between the robots;
- α_{rel}: relative angle between the two robots;
- α_{max}^{cam}: maximum camera viewing angle;
- α_{max}^{mar}: maximum angle that allows the mark to be identified;

Figure 5 shows that the relative angle (α_{rel}) between the robots is given by equation (5):

$$\alpha_{rel} = \theta_H - \theta_R \tag{5}$$

where θ_H and θ_R are the guiding angles of the humanoid and of the robot on wheels, respectively.

Making an analogy with the restrictions defined in the previous section, equation (1) refers to field of view restriction, equation (2) refers to the visibility restriction and equations(3) and (4) to the distance restriction.

Once the graph was set up, the search for a path was performed using the A^* algorithm . The estimated cost of the path that passes through a determinate vertex is given by the following equation 6:

$$f(v) = g(v) + h(v) \tag{6}$$

where $f(v)$ is the total cost of the path from the vertex of origin to the destination vertex passing through vertex v; $g(v)$ is the calculated cost of the path from the vertex of origin to vertex v and $h(v)$ is the estimated cost of the path from vertex v to the destination vertex.

Component $h(v)$ of equation (6) deserves special attention. It represents a heuristic estimation of the distance between a determinate vertex and the destination vertex. This estimation can obey the so-called admissible function, which is any function that underestimates the real value of the distance between the vertex and the destination. Nilson (1998) [10] proof that if $h(v)$ is an under-estimate that value, then the A^* algorithm ensures to find the minimum path between the source and destination.

The heuristic implemented in the algorithm is based on a Euclidian distance (equation 7). Following the definitions presented to make up equation (6) and the set of robot movements, functions $h(v)$ and $g(v)$ are defined by equations (7) and (8), respectively.

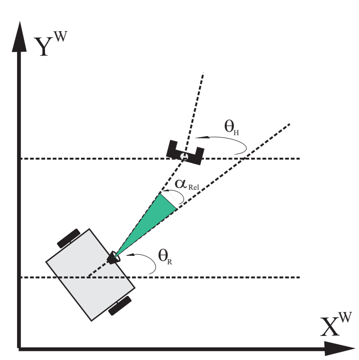

Fig. 5. Relative Angle.

$$h(v) = \sqrt{(x_H^{fim} - x_H^{atu})^2 + (y_H^{atu} - y_H^{ini})^2} \qquad (7)$$

$$g(v) = \begin{cases} g(v)^* + K_1 \cdot \Delta L_{Hum} & if, movement\ (1) \\ g(v)^* + K_2 \cdot \Delta L_{Rob} & if, movement\ (2) \\ g(v)^* + K_3 \cdot \Delta\theta_{Hum} \cdot (L_{Hum}/2) & if, movement\ (3) \\ g(v)^* + K_3 \cdot \Delta\theta_{Rob} \cdot (L_{Rob}/2) & if, movement\ (4) \\ g(v)^* + K_4 \cdot \Delta L_{Hum} & if, movement\ (5) \\ g(v)^* + K_5 \cdot \Delta L_{Rob} & if, movement\ (6) \\ g(v)^* + K_6 \cdot \Delta\theta_{Hum} \cdot (L_{Hum}/2) & if, movement\ (7) \\ g(v)^* + K_6 \cdot \Delta\theta_{Rob} \cdot (L_{Rob}/2) & if, movement\ (8) \end{cases} \qquad (8)$$

where,

- $g(v)^*$: cumulative cost;
- ΔL_{Hum}: step of linear motion of humanoid;
- $\Delta\theta_{Hum}$: step of angular motion of humanoid;
- L_{Hum}: width of the humanoid;
- ΔL_{Rob}: step of linear motion of wheel robot;
- $\Delta\theta_{Rob}$: step of angular motion of wheel robot;
- L_{Rob}: width of the wheel robot;
- K: constants;

Constants $K_i (i = 1, 2, ..., 6)$ were defined in order to consider the movements. For example, to assign a priority to the forward movement of the humanoid over its backward movement, make $K_4 > K_1$.

Concerning the planner, it must be pointed out that two discretizations were made during the implementation: one to make the number of successors of a knot infinite and the other to make the graph infinite.

To generate an infinite set of successors the movements of the robots were quantized into a set of eight elements and to make the graph finite it was considered that two positions are equal if the Euclidean distance between them are less than a threshold.

The results of the proposed planner will now be presented.

IV. RESULTS

The coefficients defined in the previous section were dimensioned as follows:

- L_{Hum} was found considering the humanoid as the circumference and measuring its diameter;
- ΔL_{Hum} and $\Delta\theta_{Hum}$ were obtained from two experiments: one which consisted of moving the humanoid forward several times and from the resulting measures determining the mean distance traveled per unit of time, and the other of making the humanoid rotate several times in a same direction and calculating the mean value of the displacement angle per unit of time; The values of L_{Rob}, ΔL_{Rob} and $\Delta\theta_{Rob}$ were obtained in a similar manner to that of the humanoid, but using the wheel robot;
- α_{max}^{mar}, D_{max} were estimated based on the work of Nogueira et al. (2006) [10] and;
- α_{max}^{cam} e D_{min} were measured by experimentation using the vision system developed for the wheel robot.

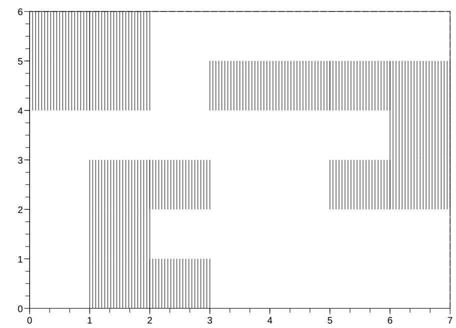

Fig. 6. Map.

To obtain the results the coefficient values used were:

- $L_{Hum} = 0.4m$; $L_{Rob} = 0.6m$;
- $\Delta L_{Hum} = 0.02m$; $\Delta L_{Rob} = 0.02m$;
- $\Delta\theta_{Hum} = 30^o$; $\Delta\theta_{Rob} = 30^o$;
- $\alpha_{max}^{cam} = 45^o$; $\alpha_{max}^{mar} = 45^o$;
- $D_{max} = 0.6m$; $D_{min} = 0.2m$;

The map by which the robot must navigate is a $7m$ x $6m$ environment containing the three fixed obstacles shown in Figure 6.

The cooperative path planning results will be presented using the idea of scenarios to characterize the problem. A scenario is described as the task of calculating a path for the humanoid from an initial position to a final position taking into account the initial position of the robot on wheels and the value of the constants considered.

Scenario 1 was set up to determine how the algorithm functions when a local minimum might exist. The configuration used was the following:

- Initial Pose of the humanoid: (0.2,0.5,90);
- Final Pose of the humanoid: (5.0,1.0,-90);
- Initial Pose of the wheel robot: (0.2,0.2,90);
- Constants: $K_1 = K_2 = K_3 = K_4 = K_5 = K_6 = 1$.

The planning result for Scenario 1 is shown in Figure 7. The path represented by dots is that of the humanoid and the dashed path is that calculated for the robot on wheels.

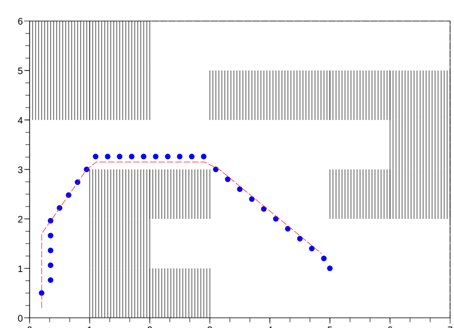

Fig. 7. Scenario 1.

Figure 8 shows a part of Scenario 1 plotted in such a way that the points calculated for the humanoid and for the robot on wheels are connected by a vector. The origin of the vector is a point calculated for the robot on wheels and the extremity is a point calculated for the humanoid. This graph is important since it illustrates the cooperative character of the planner.

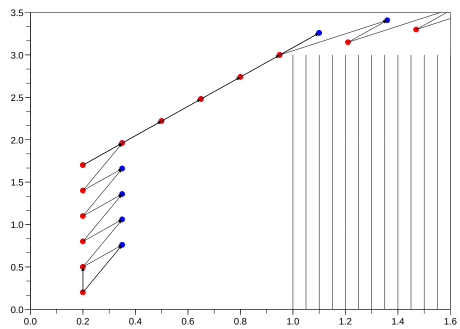

Fig. 8. Scenario 1.

The set up of Scenario 2 was performed so that the robotic system could execute a more complex and longer movement. The configuration used was as follows:

- Initial Pose of the humanoid: (0.2,0.5,90);
- Final Pose of the humanoid: (7.0,6.5,0);
- Initial Pose of the wheel robot: (0.2,0.2,90);
- Constants: $K_1 = K_3 = K_4 = K_6 = 1$ e $K_2 = K_5 = 3$.

Observe that in this Scenario the values of the constants are distinct and penalize the system when some of the robots perform a backward movement. The planning result for Scenario 2 is shown in Figure 9. The figure legend shows the dotted path to be that of the humanoid and the dashed path to be that of the wheel robot.

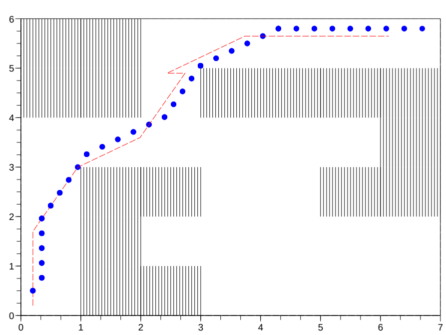

Fig. 9. Scenario 2.

Figure 9, more specifically when the humanoid is near point (3.0, 5.0), shows that the robot on wheels makes a backward movement, even with the increased final cost that this type of movement entails, since this is the only possibility of obeying the visual restrictions (Figure 10).

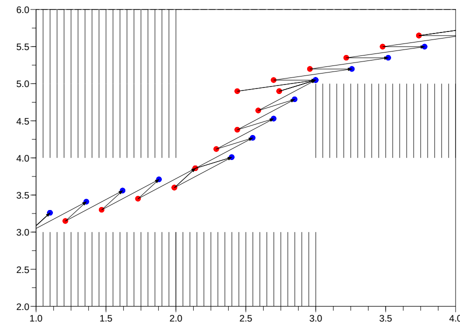

Fig. 10. Scenario 2.

V. CONCLUSIONS AND PERSPECTIVES

This study presented a path planning strategy for a heterogeneous robotic system composed of a humanoid robot and a wheel robot.

Our main contribution consists of a planner capable of calculating paths for a robotic system, obeying the nonholonomic restrictions of two robots as well as the visibility restrictions.

The results obtained were satisfactory. We tested the sensitivity of the planner in executing long and complex movements as well as in solving problems related to local minimums. In both situations the behavior of the robotic system movements proved to be intelligent. A negative aspect of the proposed solution is the elevated computational cost.

In future work we intend to:

- improve the heuristics used to incorporate the cost of energy of movement, for example;
- investigate search techniques on a graph that can implement the planner in real time;
- expand the idea to dynamic environments;

VI. ACKNOWLEDGMENTS

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