

# Non-Holonomic Navigation System of a Walking-Aid Robot.

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## Abstract

*This work presents a navigation method for a nonholonomic robot. The robot is used as a walking assistant with a person following to a specific target. During motion the path computed by the robot may be modified by the user. The method is based on a new model of “elastic bands” considering the requirements of a car-like robot moving only forward (Dubin’s model).*

Keywords: Mobile robot, Navigation, Elastic Band, Nonholonomic, Walking aid.

## 1. Introduction

Care-O-bot is the prototype of a robotic home assistant developed at Fraunhofer IPA. A first mobile platform has been built in 1998. Care-O-bot has already proved its ability to operate safely and reliably in public environments. Three robots based on the same hardware platform have been installed in March 2000 for constant operation in the “Museum für Kommunikation Berlin” where they autonomously move among the visitors, communicate to and interact with them [1].

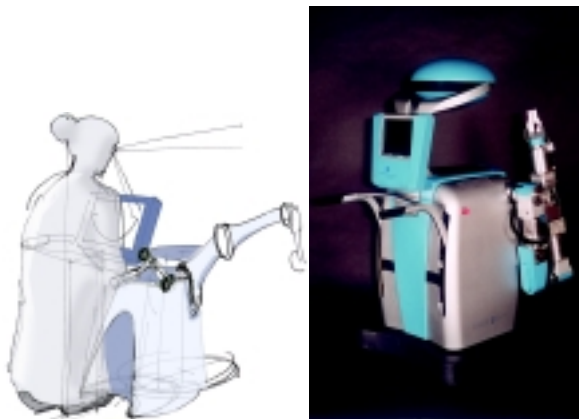


Figure 1. Care-O-bot II design and prototype.

In order to provide support for walking and standing up, two supporting handles have been attached to the mobile platform. To function as a walking aid the navigation software for such a robot must be adapted to fit dynamic and geometric

constraints on the basis of human ergonomics. The robot is not allowed to drive backwards autonomously. Also, the planned path must not include sharp turns as the user might not be able to follow such movements.

## 2. Navigation System

The navigation system is based on the elastic band approach. An elastic band is a deformable collision-free path, subjected to artificial forces.

The idea of using the elastic band method for connecting path planning and control was proposed initially by Quilan and Khatib [15] as a new framework to close the gap between global path planning and real-time sensor-based robot control. It is represented as a sequence of connected “bubbles”. The bubbles are created by examining the local freedom of the robot at configurations along this path. The elastic band deforms in real time to a short and smooth path that maintains clearance from the obstacles, enabling the robot to accommodate uncertainties and react to unexpected and moving obstacles.

Khatib, Jaoui, Chatila and Laumond [7] proposed a nonholonomic bubble band implementation for car-like robots, using an appropriate metric space. Bezier polynomials transform the elastic band into a kinematically feasible trajectory.

Based on similar criterium, a new model of elastic band has been develop for nonholonomic car-like robots that can move only forward (Dubin’s model).

## 3. Bubble Band for a Dubin’s car

An elastic band is a continuous path covered by bubbles. A bubble represents all configurations  $p$ , which a robot with the given restrictions can reach from its current configuration  $q$  without collision.

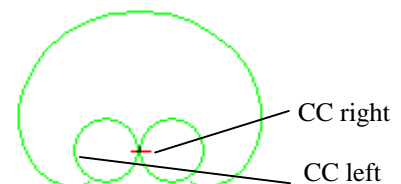


Figure 2. Bubble for a Dubin’s car.

The radius  $r$  of a bubble is defined as the minimum nonholonomic distance from the current configuration to the closest obstacle. An appropriate metric for nonholonomic distance evaluation is used. The nonholonomic distance  $B(q,r)$  from a configuration to a point or a segment was solved in [14]:

$$B(q,r) = \{ p \in \mathfrak{R}^N : \|q - p\| < r(q) \}$$

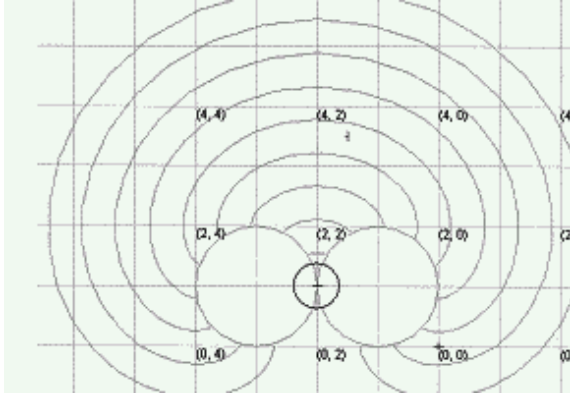


Figure 3. Set of reachable configurations for a Dubin's car

A bubble for a Dubin's car has two so called CC regions (see Figure 4). Given a configuration  $q(x,y,\theta)$ , the corresponding CC regions are defined by the set of configurations lying inside the circles with a radius the minimum turning radius of the robot, tangent at  $q$  to the robot orientation  $\theta$ . The areas "CC left" and "CC right" are situated on the left and right side of the robot, respectively. These CC regions will be kept into account when generating optimal paths for the robot.

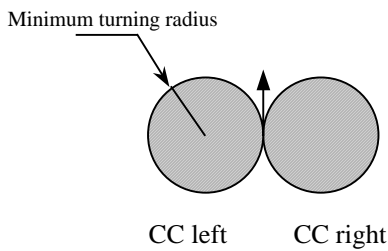


Figure 4. CC regions for a Dubin's car.

To optimize the distance between bubbles, we impose the following restriction: "The opposite CC regions between two bubbles must not overlap". The force model of the elastic band must be able to handle this restriction (see Figure 5).

Each bubble can be modified according to two kinds of forces – external and internal forces. External forces push the path away from obstacles; internal forces remove any possible slack in the path.

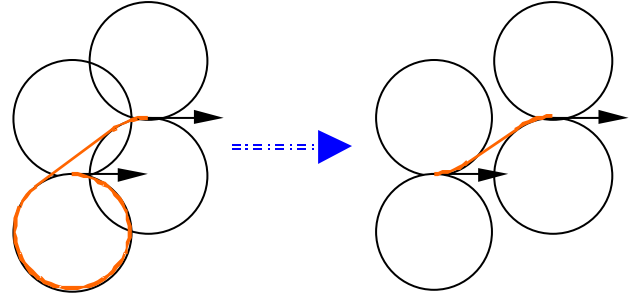


Figure 5. Optimized distance between bubbles.

### 3.1. External forces

External forces move the bubble band away from obstacles. They are calculated creating a local potential field  $\phi(x,y)$  as the maximum potential generated by all obstacles, or – what is the same – the potential generated by the closest obstacle.

$$\phi(x,y) = \max \{ \phi_i(x,y) \}, i = 1,2,3...$$

For  $d$  being the distance to the nearest obstacle,  $w$  being the limit specified for obstacles to be considered, the following potentials are calculated for each obstacle:

$$\phi(x,y) = \tan\left(\frac{\pi}{2}\left(1 - \frac{d}{w}\right)\right) \quad (d < w)$$

$$\phi(x,y) = 0 \quad (d \geq w)$$

The generated potentials come close to infinite near the obstacles ( $d \rightarrow 0$ ). The potentials become zero when the distance to all obstacles is larger than the limit  $w$ .

The external force  $F_{ext}$  affecting each bubble is the negative gradient vector of the potential field, evaluated in the origin  $(x,y)$  of the bubble.

$$F_{ext} = -\nabla\phi(x,y)$$

### 3.2. Internal forces

Internal forces contract the band and push away the opposite CC regions between bubbles. A model with three forces has been proposed successfully.

We denote "RL-forces" the forces, which push away the left CC region of the current bubble from the right CC regions of the previous and next bubble. In the same way, we denote "LR-forces" the forces, which push away the right CC region of the current bubble from the left CC regions of the previous and next bubble. We denote "C-forces" the forces of attraction between centers of adjacent bubbles (see Figure 6).

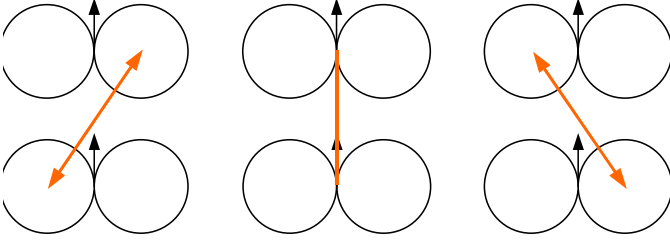


Figure 6. Internal forces between bubbles.

With  $q_L$ ,  $q$  and  $q_R$  being the center of the left CC region, the bubble and the right CC region respectively, the following equations specify the forces system.

$$LR_i = \frac{q_{Li} - q_{Ri-1}}{|q_{Li} - q_{Ri-1}|} \frac{1}{r_{i-1}} P(q_{Li}, q_{Ri-1}) + \frac{q_{Li} - q_{Ri+1}}{|q_{Li} - q_{Ri+1}|} \frac{1}{r_i} P(q_{Li}, q_{Ri+1})$$

$$RL_i = \frac{q_{Ri} - q_{Li-1}}{|q_{Ri} - q_{Li-1}|} \frac{1}{r_{i-1}} P(q_{Ri}, q_{Li-1}) + \frac{q_{Ri} - q_{Li+1}}{|q_{Ri} - q_{Li+1}|} \frac{1}{r_i} P(q_{Ri}, q_{Li+1})$$

$$C_i = \frac{q_{i-1} - q_i}{r_{i-1}} + \frac{q_{i+1} - q_i}{r_i}$$

$$F_i = K_r \cdot (LR_i + RL_i) + K_c \cdot C_i$$

The resulting internal force affecting each bubble is the sum of its LR, C and RL forces. LR and RL forces are multiplied with a repulsion factor  $K_r$ , C forces are multiplied with a contraction factor  $K_c$ .

All forces are previously scaled depending on the radius  $r$  of the current and previous bubble. This is important to get independence of the size of the bubbles, to avoid bubble migration along the elastic band, and to avoid continuous creation and elimination of a bubble.

LR and RL forces are further scaled by the potential function  $P(q_L, q_R)$ . This function returns a real number depending on the distance between CC regions. The return value comes close to infinite for CC regions being too close, thereby avoiding overlapping bubbles. The potential comes close to zero for bubbles being further apart than a given maximum distance.

The orientation of a bubble is modified depending on the torque  $T$  – computed as the momentum affecting the bubble due to LR and RL forces. The angle modification  $\Delta\alpha$  is calculated as this torque scaled by a rotation factor  $k_r$ .

$$T_i = LR_i \times (q_{Li} - q_i) + RL_i \times (q_{Ri} - q_i)$$

$$\Delta\alpha_i = k_r T_i$$

### 3.3. Virtual forces

A third kind of forces can be generated by user input, to modify the path followed by the robot. User input here means that a person can “push” or “pull” the robot in a certain direction. The forces applied are read through force/torque sensors

attached to the platform and transferred directly to the elastic band algorithm.

### 3.4. Disconnected/Redundant bubbles

The origin of a bubble must always be inside the previous one, except for the first bubble of the band. When the origin of a bubble is outside all other bubbles, it is called “disconnected”.

To find out whether a bubble is disconnected, the radius of the previous bubble  $r_{i-1}$ , is compared with the nonholonomic distance (nhd) between origins  $nhd(p_{i-1}, p_i)$ . A small margin value  $\epsilon_c$  is used to avoid creation-elimination loops. When a bubble is disconnected, the shortest path between the current and previous bubble is calculated and a new bubble is created in the middle.

Disconnection condition:

$$nhd(p_{i-1}, p_i) \geq r_{i-1} - \epsilon_c$$

When a bubble is detected between two connected bubbles, it is “redundant” and can therefore be deleted from the band. A small margin value  $\epsilon_o$  is used to avoid creation-elimination loops.

Redundancy condition:

$$nhd(p_{i-1}, p_{i+1}) \leq r_{i-1} - \epsilon_o$$

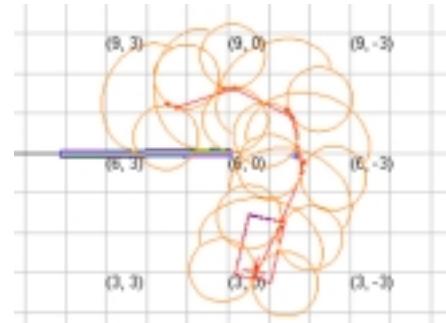


Figure 7. Connected bubble band for a Dubin's car

### 3.5. Elastic band creation

The elastic band is initialized with a small number of configurations, the path returned by the path planner. Then, the band is checked to detect disconnections. When a disconnection is detected, a new bubble is created. This process is repeated until all bubbles are connected. A connected bubble band for a Dubin's car is shown in Figure 7.

### 3.6. Elastic band modification

The elastic band is modified cyclically in three steps:

1. Check for disconnections
2. Check for redundancy
3. Modify configurations

Each bubble is modified according to the given forces, external, internal and virtual:

$$F_{res} = F_{ext} + F_{int} + F_{virt}$$

$$Pos_{new} = Pos_{Old} + \delta F_{res}$$

A bubble might change its position due to the given forces. For the modified bubble configuration, the size of the bubble and the nonholonomic distance to the obstacles must be recalculated.

### 3.7. Smoothing

Once the bubble band is set, the path to execute is the concatenation of all bubbles' centers. A Bézier algorithm is used to track the path smoothly. The control points are set dynamically depending of the orientation and position of the bubbles, based on experimental factors in order to get a smooth transition within the nonholonomic area.

## 4. Path planner

The elastic band must be initialized with an initial path, connecting the start configuration with the goal configuration. Taking in consideration that:

*"If there is a nonholonomic path connecting two different configurations, also exists a holonomic path connecting those configurations"*

A planner based on a visibility graph is used to get the shortest path connecting the start with the goal configuration. The path is checked to validate whether it is suitable to be modified, in order to become a nonholonomic path, if not, the current path is rejected and the graph is searched again. The process shortest path – rejected path is repeated until a suitable path is found.

The path is used to initialize the elastic band, which will evolve to a nonholonomic state if possible.

The planning is computed in the 2D workspace without computing the complex C-Space. The A\* algorithm is used for efficient graph searching.

Several test were made with both the described planner and a random planner.

## 5. Experimental Results

Some experimental results of the elastic band algorithm for a Dubin's car are displayed in Figure 8, Figure 9 and Figure 10. The walking aid assistant respond quickly to any obstacle detected on the planned path. The trajectory is modified to guide the person along a feasible way. Applying preassure to the sensors on the walking aid supporters, the person may modify the path creating artificial forces that influence the elastic band state, by appropriate sensors on the sticks. In Figure 9, the

elastic band is initialized using a nonholonomic planner. In Figure 10, the elastic band is initialized with a random planner no suitable for a nonholonomic planning, however, if possible, the band evolves itself to a nonholonomic state. This feature allows the flexible use of the best path planner depending on the enviromental conditions.

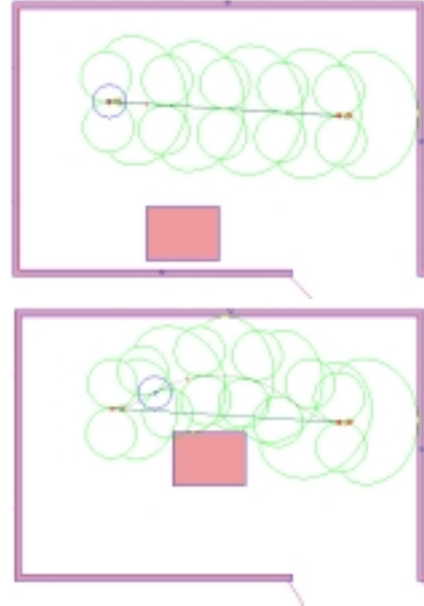


Figure 8. Dynamic obstacle avoidance

## 6. Conclusion and Outlook

The implementation of a navigation system based on a new model of elastic band has been described. The algorithm can be used on different kinds of robots, geometric and kinematic properties can be activated and deactivated on the fly.

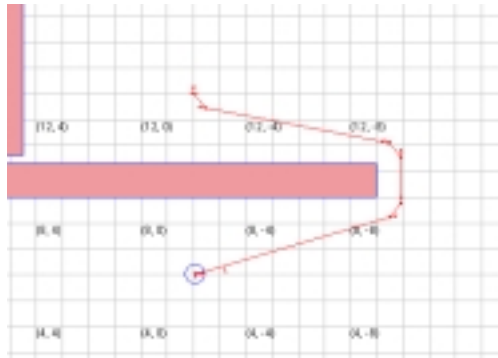
The algorithm has successfully been implemented on the intelligent mobile home assistant Care-O-bot, which is also used as an intelligent walking aid [4] (Figure 11). Reactive path modification not only due to dynamic obstacles but also in reaction to user input through force sensors attached to the walking handles while following a path is included.

The described force system model is very efficient and the algorithm is very fast. When running the program on a Pentium III processor under Windows 2000, the local modification of the elastic band in the working area of the robot takes less than 100 milliseconds.

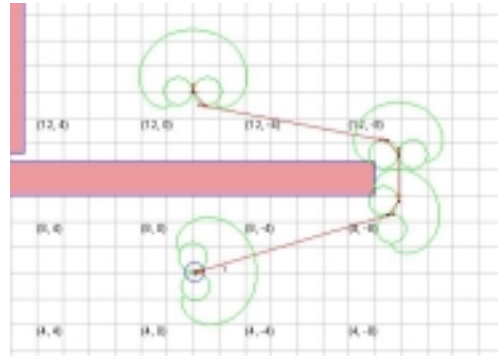
## 7. Acknowledgements

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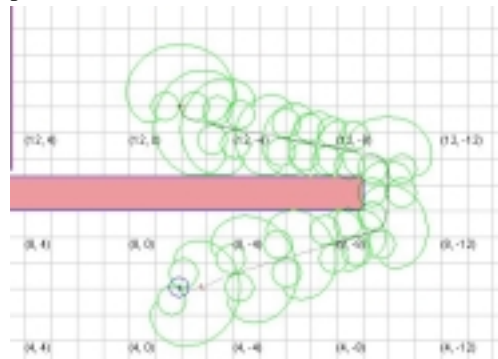
Step 1: The planner returns four configurations.



Step 2: A bubble is created in each configuration



Step 3: The band is covered with connected bubbles



Step 4: The band is optimized

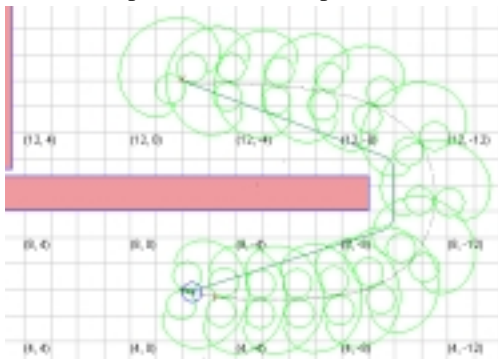
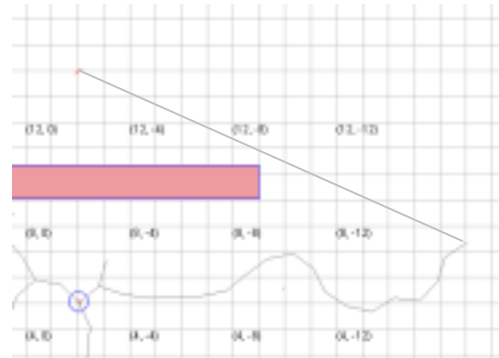
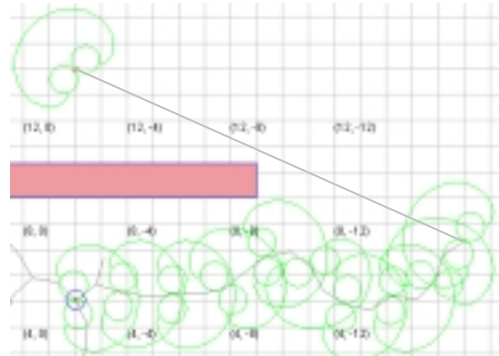


Figure 9. Path planner based on [6]

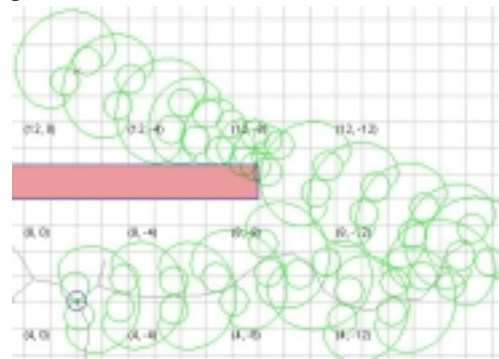
Step 1: Path returned by a random planner



Step 2: A bubble is created in each configuration



Step 3: The band is covered with connected bubbles



Step 4: The band is optimized

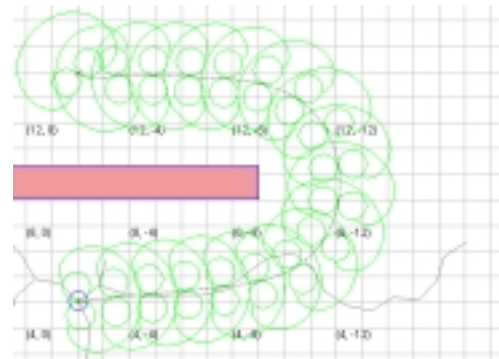


Figure 10. Random planner based on [9]



Figure 11. Intelligent walking aid Care-o-Bot II ©

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