Springer

Journal of Mechanical Science and Technology 22 (2008) 2090~2098

Journal of
Mechanical
Science and
Technology

www.springerlink.com/content/1738-494x
DOI 10.1007/s12206-008-0718-9

Collision-free motion coordination of heterogeneous robots [†]

Nak Yong Ko[1], Dong Jin Seo[2,*] and Reid G. Simmons[3]

[1]*Dept. Control, Instrumentation and Robot Eng., Chosun Univ., Korea*
[2]*The Robotics Institute, RedOne Technologies, Korea*
[3]*The Robotics Institute, Carnegie Mellon Univ., USA*

(Manuscript Received February 13, 2007; Revised November 30, 2007; Accepted July 21, 2008)

Abstract

This paper proposes a method to coordinate the motion of multiple heterogeneous robots on a network. The proposed method uses prioritization and avoidance. Priority is assigned to each robot; a robot with lower priority avoids the robots of higher priority. To avoid collision with other robots, elastic force and potential field force are used. Also, the method can be applied separately to the motion planning of a part of a robot from that of the other parts of the robot. This is useful for application to the robots of the type mobile manipulator or highly redundant robots. The method is tested by simulation, and it results in smooth and adaptive coordination in an environment with multiple heterogeneous robots.

Keywords: Collision-free motion coordination; Multiple robots; Elastic force; Priority

---

1. Introduction

We propose a method to coordinate the motion of multiple heterogeneous robots. Recently, with the rapid advancement of information technology, multiple robots work in a common workspace, at times communicating with each other [1, 2]. To facilitate the use of multiple robots, it is crucial to coordinate the motion of the robots preventing interference between the robots. For coordination, the proposed method uses prioritization and avoidance. Priority is assigned to each robot, and a robot with lower priority avoids other robots of higher priority. To avoid collision with other robots, elastic force and potential field force are used.

As for the collision avoidance of robots, there have been many researches. The artificial potential field approach [3] is popular method for collision avoidance of mobile robots, and it has many variations for improvement [4, 5]. While it is easy to apply and widely used, its local minimum problem requires some additional means to avoid traps or oscillatory situations. Other approaches considering the path as the piecewise continuation of circular path segments [6, 7] and the dynamic windows approach [8] produce a fast and smooth trajectory. Sometimes, many different approaches are combined to yield more comprehensive and robust performance. As an example, geometric search and elastic force are adopted to yield the ASL method [9].

The proposed method uses the physical properties of elasticity and potential field to avoid other robots of higher priority. The elastic force is one of the concepts drawn from physical phenomena, and used for collision avoidance [10, 11]. Elasticity usually exerts a force which keeps the shape of an elastic material in its original shape if distorted. On the other hand, the potential field exerts a distorting force against the objects of the same polarity. The potential field force is used for repulsive force from other robots, while the elastic force is used to guide the robot through an efficient trajectory. In the field of robot motion con-

---

[†] This paper was recommended for publication in revised form by Associate Editor Jong Hyeon Park

[*] Corresponding author. Tel.: +82 62 373 2024, Fax.: +82 62 373 2022
E-mail address: commidi@gmail.com

trol, the robot tries to keep its trajectory toward a goal pose while the other robots intrude to distort the robot's trajectory. The term *pose* means position and orientation of a mobile robot and the configuration of a manipulator. The concept of elasticity is applied for multiple robot motion coordination, and the conventional elastic force based approach is improved.

We modify the previous elastic force based methods to make improvement for application to multiple robot cooperation. The first improvement is the use of the approach to keep the end-effector motion unaffected by avoidance motion. It means that the method can be used to control the end-effector motion specified for task completion while the robot avoids other robots. This improvement is possible when the robot is redundant and has sufficient degrees of freedom. Since the mobile manipulator used in our research has 7 degrees of freedom, it is made possible to move the end effector through straight line trajectory while the mobile base moves for collision avoidance.

The second improvement is the use of the approach separately to parts of a robot. For example, for collision-free motion coordination of a mobile manipulator, we apply the avoidance approach to the mobile base and to the manipulator separately. The method can be applied separately in the case where only the initial configuration and goal configuration of the mobile manipulator are given and the trajectory between these configurations is not restricted.

In the applications, the method is applied separately to the mobile base and manipulator when the mobile base is nonholonomic. A nonholonomic mobile base cannot follow the collision-free path calculated by the method applied in its entirety because the orientation and position are interdependent. In this case the manipulator cannot move as desired because it is attached to the base whose motion deviates from the desired trajectory. As a result, the manipulator can collide with other robots. So the manipulator motion should be planned separately from the base motion to avoid collision even though the base deviates from the planned trajectory. Besides the benefit discussed above, the separate application reduces the computational burden due to high dimensionality.

Section 2 explains the overall procedure. Also, it discusses a method using the elastic force and potential field force for motion coordination. Sections 3 and 4 describe improvements over previous approaches for application to multiple robot systems. Section 5 shows some simulation results of the proposed method. Section 6 concludes the paper with a discussion of the method.

2. Motion coordination procedure using elastic force and potential field force

2.1 Motion coordination procedure

We briefly introduce the motion coordination procedure. The first step sets a priority to each robot in the system. Then, each robot moves from its initial pose to final pose avoiding collision with other robots of higher priority.

For collision avoidance, elastic force and potential field force are used. The elastic force guides the robots to their goal poses, while the potential field force repels the robots from each other. Whereas the usual potential field method attracts each robot to its goal pose using goal directed potential field force, the proposed method uses elastic force for that purpose. The elastic force not only guides the robots to their goal poses, it also works to restore a robot's configuration when other robots go away from it.

Each robot considers other robots of higher priority as obstacles and it avoids other robots and obstacles. The details of the procedure can be found in [11]. Priority is also needed for better motion coordination of the robots. If there is no priority, that is, if the robots have the same priority, the robots move less efficiently than the case where priority is given to each robot. In section 5, the simulation result which uses priority is compared with the result which doesn't use priority.

Higher priority is assigned to the robot whose motion should be planned independently of other robots. For example, if a robot should move as straight as possible driven by the elastic force, independently of other robots, and the motion of the robot should not be intruded on by other robots, then higher priority is assigned to the robot. Since a robot with lower priority has to avoid the robots with higher priority, its trajectory is dependent on the motion of other robots with higher priority.

2.2 Elastic force and repulsive potential field force acting on a control point

Elastic force and potential field force are briefly discussed to explain the improvement over previous works for coordination of multiple robots which work for task completion without collision. On the robot, some points called the control points are set. On the control points, the elastic force and repulsive potential field force are exerted. Although it is most desirable to apply and spread the elastic force and repulsive potential field force at every point throughout the body of the robot, only several points should be chosen for practical application.

The control point at a link should be chosen so that the joint torque at the joints below the link due to the elastic force and potential field force exerting on the control point is as close as possible to the joint torque due to sum of the elastic force and potential field force exerted on every point of the link. In mathematical expression, the control point at the i-th link should be chosen to minimize the torque difference

$$\left| \mathrm{J}^T(\mathbf{p}_i)\cdot f(\mathbf{p}_i) - \lim_{M\to\infty}\frac{1}{M}\sum_{k=1}^{M}\mathrm{J}^T(\mathbf{p}_k)\cdot f(\mathbf{p}_k) \right| \qquad (1)$$

Here M is the number of infinitesimal points in the i-th link. $J\ (\mathbf{p}_k)$ is the Jacobian matrix relating the velocity of the point $\mathbf{p}_k$ to the angular velocity of the joints below the i-th link. $f\,(\mathbf{p}_k)$ is the sum of elastic force and potential field force exerting on the point $\mathbf{p}_k$.

It is also recommended that the control points be chosen so that the whole body is collision-free if the control points are collision-free. Fig. 1 is the mobile manipulator called a Bullwinkle which is used for the application and Fig. 2 shows the control points assigned to Bullwinkle. We use the notation ${}^j\mathbf{p}_i$ for a control point. ${}^j\mathbf{p}_i$ represents the i-th control point in the j-th way pose. The superscript represents the order of a way pose, and the subscript represents the order of the control point in the way pose. The control point ${}^j\mathbf{p}_b$ represents the control point on the mobile base in its j-th way pose when the robot includes a mobile base.

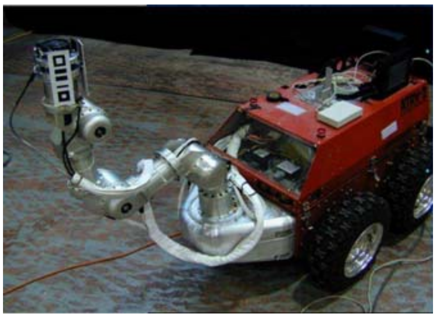


Fig. 1. One of the robots used in the application. The robot Bullwinkle has skid-steered mobile base and five joint manipulator.

The elastic force ${}^j\mathbf{ef}_i$ exerting to the control point ${}^j\mathbf{p}_i$ is as follows.

$${}^j\mathbf{ef}_i = k_c\left(\frac{d_{j-1,j}}{d_{j-1,j+1}}\left({}^{j+1}\mathbf{p}_i - {}^{j-1}\mathbf{p}_i\right) - \left({}^{j}\mathbf{p}_i - {}^{j-1}\mathbf{p}_i\right)\right) \qquad (2)$$

In the equation, $d_{j-1,j}$ is the distance between ${}^{j-1}\mathbf{p}_i$ and ${}^j\mathbf{p}_i$. $d_{j-1,j+1}$ is the distance from ${}^{j-1}\mathbf{p}_i$ to ${}^{j+1}\mathbf{p}_i$ via ${}^j\mathbf{p}_i$. k_c is the coefficient which determines elastic force. The larger the k_c is, the straighter the trajectory of the control point becomes. If we set different values of k_c to each control point, we can control the flexibility of the trajectories corresponding to the individual control points. This can be used to control the end-effector motion as specified for task completion while the robot avoids other robots. We call the motion as "task-consistent" motion, and it will be discussed in the section 2.3

While the elastic force connects the initial pose to the final pose through way poses, the potential field force works to push the trajectory away from other robots. The following shows the repulsive potential field $V_{rep}\ ({}^j\mathbf{p}_i)$ and repulsive potential field force ${}^j\mathbf{rf}_i$ at the control point ${}^j\mathbf{p}_i$.

$$V_{ref}({}^j\mathbf{p}_\mathrm{i}) = \begin{cases} \frac{1}{2}k_r(d_r - d({}^j\mathbf{p}_i))^2 & if\ d({}^j\mathbf{p}_i) < d_r \\ 0 & otherwise \end{cases}$$

$${}^j\mathbf{rf}_i = -\nabla V_{ref}({}^j\mathbf{p}_i) = k_r(d_r - d({}^j\mathbf{p}_i))\frac{{}^j\mathbf{p}_i - \mathbf{p}_0}{\left\|{}^j\mathbf{p}_i - \mathbf{p}_0\right\|}$$

In the equation, d_r is the radius of the range under the influence of the repulsive potential field. $d\ ({}^j\mathbf{p}_i)$ is the shortest distance between the control point ${}^j\mathbf{p}_i$ and the location $\mathbf{p}_o$ of the other robot relevant to collision. k_r is the coefficient for the repulsive potential field force to the distance.

The calculation of the exact potential field force to a robot requires integration of the potential field force

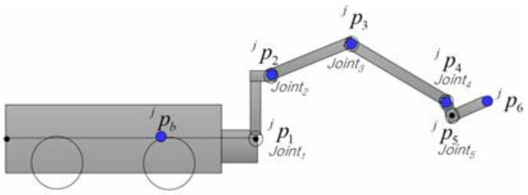


Fig. 2. Control points assigned onto the Bullwinkle. ${}^j\mathbf{p}_i$ represents the i-th control point on the robot in its j-th way pose.

acting on all the points of the robot, that is, integration over the volume of the robot. For practical implementation, we approximated the mobile base as a point. Instead of approximation as a point, the shape of other robots is augmented to compensate for the point approximation. Thus, the robots which are to be avoided are modeled as configuration space objects.

The net force ${}^j\mathbf{f}_i$ which is exerted on the control point ${}^j\mathbf{p}_i$ is the sum of the elastic force and the repulsive potential field force.

$$ {}^j\mathbf{f}_i = {}^j\mathbf{ef}_i + {}^j\mathbf{rf}_i,\ \ for\ i = 1,2,...,n $$

(n : The number of control points on the robot)

Once the elastic force and potential field force are found, we change the way pose according to the joint torques induced by the forces ${}^j\mathbf{f}_i$ (i = 1, 2,…, n). The modified way poses form the modified trajectory which the robot should follow toward its goal pose without collision with other robots of higher priority.

The elastic force and potential field force do not control the robot directly. The robot changes its configuration through the joint motion. So, it is required to calculate the joint torques or forces due to the elastic force and potential field force. The joint torque or forces are calculated by using the Jacobian matrix from the elastic force and potential field force acting on the control points.

$$ \tau_i = \mathbf{J}_i^T \mathbf{f}_{i+1} $$

Here, the vector $\tau_i = [\tau_1, \tau_2, ..., \tau_i]^T$ consists of the torques on the joints 1,2,…,i and the vector $f_{i+1} = [f_{i+1,x}, f_{i+1,y}, f_{i+1,z}]^T$ represents the force acting on the control point $\mathbf{p}_{i+1}$. The vector $\mathbf{f}_{i+1}$ is the sum of the elastic force and repulsive force acting on the control point $\mathbf{p}_{i+1}$. The matrix $\mathbf{J}_i$ is the $3 \times i$ Jacobian matrix satisfying the following relationship,

$$ \dot{\mathbf{p}}_{i+1} = \mathbf{J}_i \dot{\mathbf{q}}_i $$

where $\mathbf{p}_{i+1} = [p_{i+1,x}, p_{i+1,y}, p_{i+1,z}]^T$ is the position vector of the $(i+1)$-th control point and $\mathbf{q}_i = [\theta_1, \theta_2, \ldots, \theta_i]^T$ is the joint variable vector.

The joint torque or forces are used to calculate joint variables of the new way pose which is subject to the elastic force and potential field force for collision avoidance and goal directed motion. Thus, the joint torque or forces lead the joints through collision-free trajectory toward a goal configuration.

2.3 Improvement for task completion avoiding collision with other robots

As we set k_c of the elastic force in Eq. (2) higher for a control point than those for other points, the trajectory for the point will become straighter than other points. Suppose that k_c is assigned higher value to the control point at the end effector than to the other control points. Then the end-effector trajectory will move straighter toward its goal location, while other points detour for collision avoidance. In the extreme case that k_c is infinity for the end effector, the end effector moves straight from its initial position to the final position. Only the other part of the robot works for collision avoidance. In this way, some part of the robot can follow a specific path while other parts move through flexible path for coordination and collision avoidance. If we set k_c = 0 for a control point, then the control point moves completely dependent on the motion of the neighboring control points.

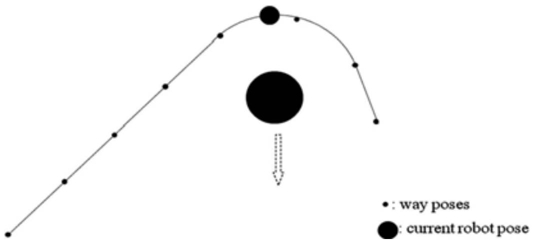
If it can be assumed that straight line motion of the end effector is one of the typical examples of task requirements, then the straight end-effector motion unaffected by avoidance motion can be called task-consistent motion. Here, “task-consistent” means that the straight line motion is “in agreement with the task requirement.” Besides, the task-consistent motion is possible only when the robot is redundant and has sufficient degrees of freedom; and it is possible only when the end effector trajectory is within the range of work space which is dependent on the pose of the mobile base. Section 5 will show the result of the proposed improvement.

3. Use of way pose for tracing a trajectory

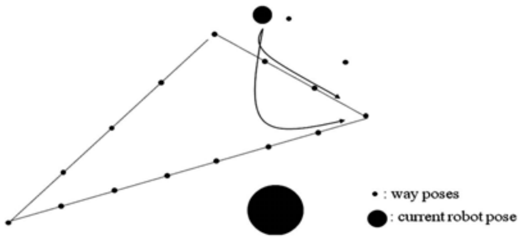
3.1 Basic approach: fixing the initial pose

The way poses represent the trajectory of the motion. The method drives the robot through the way poses in sequence. Once the robot reaches a way pose, it then moves toward the next way pose. As the robot gets closer to the goal, the number of way poses passed through will increase and the number of remaining way poses waiting to be passed through decreases. This process repeats until the robot passes the last way pose and reaches the final goal pose.

Though this method is easy and straightforward



(a) The other robot is moving down



(b) Two possible trajectories after the other robot moves away

Fig. 3. Problem of the basic application presented in the section 3.1. The robot tries to go through ${}^5\mathbf{p}'_i$, ${}^6\mathbf{p}'_i$, ${}^7\mathbf{p}_i$ rather than through ${}^5\mathbf{p}''_i$, ${}^6\mathbf{p}''_i$, ${}^7\mathbf{p}_i$.

application of the proposed approach, it can create some problems, one of which is explained in Fig. 3. If the other robot moves away from the straight path between the robot and the goal pose, then the elastic forces work to make the trajectory straight. So, as shown in Fig. 3(b), the way poses ${}^5\mathbf{p}_i$ and ${}^6\mathbf{p}_i$ move to ${}^5\mathbf{p}'_i$ and ${}^6\mathbf{p}'_i$ respectively. Then the robot suddenly tries to change heading to go through ${}^5\mathbf{p}'_i$, ${}^6\mathbf{p}'_i$, ${}^7\mathbf{p}_i$. In this case, evidently it's better to move through the path ${}^5\mathbf{p}''_i$, ${}^6\mathbf{p}''_i$, ${}^7\mathbf{p}_i$.

3.2 Improvement over the basic approach

The proposed basic approach discussed in the previous section (Sect. 3.1) can be improved for various applications. The basic approach fixes the initial and final pose and keeps the number of the way poses constant. As the first modification, we reset the initial pose at every sampling time as the present pose of the robot, instead of keeping the initial pose fixed. In this case, the robot always pursues the way pose next to the initial pose. So, the number of way poses remaining to be passed through does not decrease even though the robot approaches the goal pose. On the other hand, the space between the way poses becomes narrower as the robot moves toward the goal pose.

With this modification, the problem mentioned by the Fig. 3 can be solved and the robot motion becomes smoother as the robot approaches the goal pose. Eventually, the initial pose as well as the way poses will converge to the goal pose. When the robot approaches the goal pose close enough, the way poses will concentrate around the goal pose, and the robot will substantially stay still.

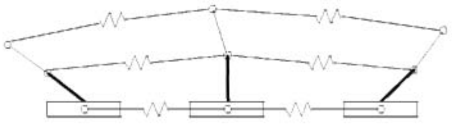
The first modification also makes other improvements. Even after the robot reaches the goal pose, the way poses can move away from the goal pose if there is another robot intruding on the robot. Unlike the case of fixing the initial pose, the robot resumes avoidance motion even after it already has reached near the goal pose. If the other robot moves away from the goal pose again, the robot comes back to the goal pose. This function of "resuming motion" is made possible because the way poses are kept not passed through. If the way poses have already been passed through, the robot will not pursue them even though the trajectory is changed by the adjustment of the way poses which are pushed away by the other robots.

The second modification is to keep the passed way poses fixed, that is, not to apply the elastic force and potential field force to the way poses which have been already passed. The elastic force and potential field force modify only the way poses remaining to be traced. This modification also solves the problem of the basic application method depicted in Fig. 3. It drives the robot through the path ${}^5\mathbf{p}''_i$, ${}^6\mathbf{p}''_i$, ${}^7\mathbf{p}_i$ instead of the path ${}^5\mathbf{p}'_i$, ${}^6\mathbf{p}'_i$, ${}^7\mathbf{p}_i$.

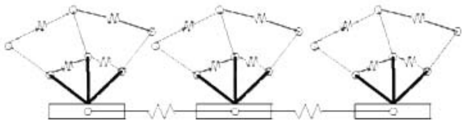
There can be other variations. In some cases, it is necessary to add extra way poses or delete some way poses between two way poses. Also, if the goal pose is too far from the initial pose, then we divide the task in some segments and apply the method segment by segment in sequence.

4. Application of the approach to the base and manipulator in parts

In this section we discuss separate application of the method to parts of the robot. For example, in case of a mobile manipulator, suppose that we separate the base motion from the motion of the manipulator. Then the nonholonomity of the base does not affect the motion of the manipulator, and it will be easier to plan the motion of the base as well as the manipulator. In case of collision avoidance problem, both the base and the manipulator are free to choose their trajectory provided that they start from their initial pose and end



(a) Unified application



(b) Application of the approach to the base and manipulator in parts

Fig. 4. In (a), the motion of the base and manipulator is considered in its integrity. In (b), the base motion is planned in no relation to the manipulator motion. The nonholonomic constraint of the base does not influence the motion of the manipulator.

at their goal pose. They are required only to avoid collision on their way to the goal pose. So it is possible to separate the motion planning of the base and manipulator. Thus, we can apply the proposed approach to the mobile base and the manipulator independently. Fig. 4 compares the two application methods. In (a), the motion of the base and manipulator is considered as an integrated unit, while in (b), they are considered separately.

In the case of the robot Bullwinkle (Fig. 1) which is used in this research, the isolation of the motion control is useful because we can easily take the nonholonomity of the base into consideration when we plan the base motion. By separating the motion of the nonholonomic base from the motion of the manipulator, the nonholonomity of the base does not affect the motion of the manipulator.

5. Simulation results

The proposed method is applied for motion coordination of multiple robots of different types. The robots are a mobile manipulator called Bullwinkle, mobile robot called Xavier [12], Nomad Super Scout II, and PeopleBot DX. Among them, Bullwinkle and Xavier have been used for coordinated motion of multi-agent teams in a project at CMU [13].

In the first example, the robots Bullwinkle, Nomad Super Scout II, and PeopleBot DX are used to show the effect of the priority assignment. Fig. 5 shows the coordinated motion with no priority while Fig. 6 shows the coordination with priority. The line connecting a starting pose to a goal pose is the elastic chord which represents the planned path. The robots should follow the path for coordination. In both examples, each robot starts its motion with the same pose, and ends at the same pose. With no priority, each robot avoids the other two robots, and inefficient trajectories result in.

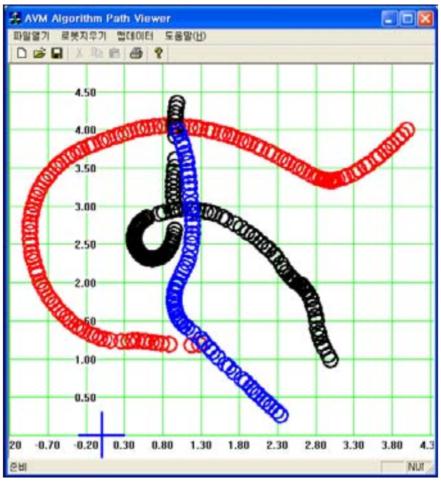


Fig. 5. No priority is given to each robot. Since the robots don't have motion priority, all the robots do the avoidance motion. However, it complicates the coordination and results in inefficient motion.

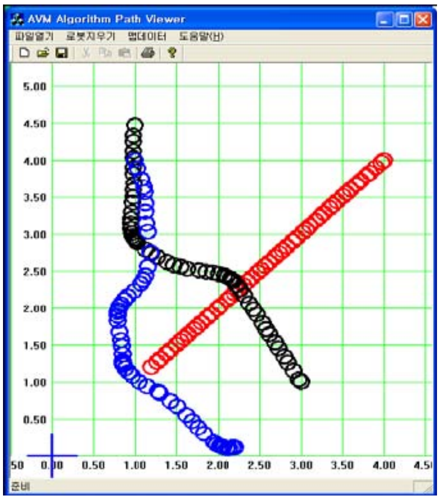


Fig. 6. Priority is assigned to each robot. The starting poses and goal poses of the robots are the same as those for the Fig. 5. The highest priority is assigned to the Bullwinkle, second priority to the Nomad Super Scout, and the third priority to the PeopleBot.

With priority, the robots exhibit more efficient trajectory than the case with no priority. In Fig. 6, the highest priority is assigned to the Bullwinkle, second priority to the Nomad Super Scout, and the third priority to the PeopleBot. The Bullwinkle goes straight because it has the highest priority. Only the PeopleBot avoids collision with the other two robots. The Nomad Super Scout avoids only the Bullwinkle.

Fig. 7 shows the result of the basic application of the method. Fig. 8 shows the effect of the first modification, and Fig. 9 shows the effect of the second modification, which is explained in section 3.2. In the basic application, the change of the elastic chord is not continuous. So, the Bullwinkle is commanded to follow a trajectory which is not connected to the current configuration of it. Thus, it exhibits bumpy motion (Fig. 7). By contrast, the elastic chord originates from the current configuration with the first modification. So, it does not result in jerky motion. As shown on the Fig. 8, PeopleBot changes its path smoothly as the Nomad Super Scout moves away from its path toward the goal position.

With the second modification, a part of the elastic chord which the robot has already passed does not change its shape (Fig. 9). Since the space between two way poses is wider than that for the first modifi-

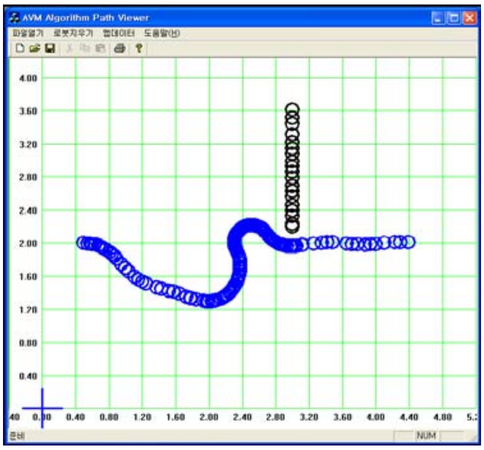


Fig. 7. Higher priority is assigned to the Nomad Super Scout. Though the Nomad Super Scout moves away from the PeopleBot's path, the usual method of way pose results in jerky motion of the PeopleBot, which as is expected in section 3.1.

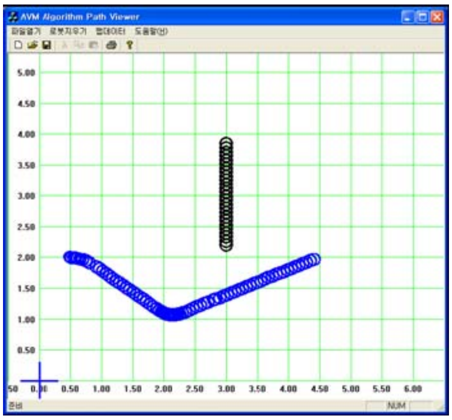


Fig. 8. These figures show the results of the first modification which is suggested in section 3.2.

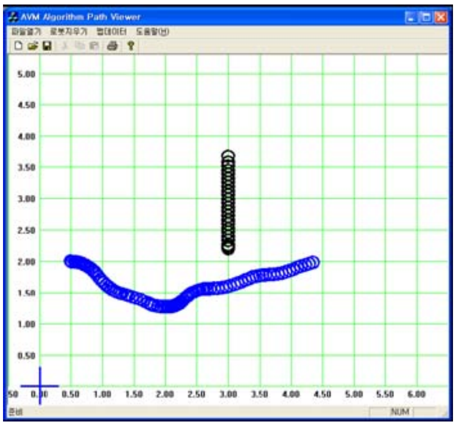
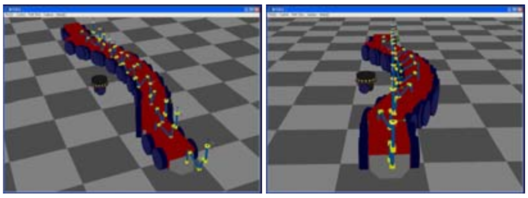
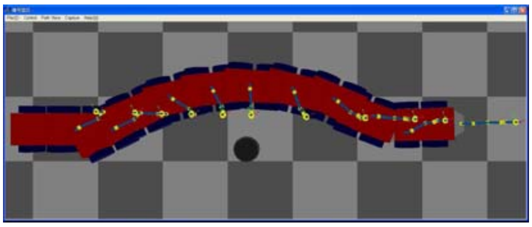


Fig. 9. These figures show the results of the second modification which is suggested in section 3.2. There remains a little jerky motion compared with the first modification shown on Fig. 8.



(a) Front lateral view (b) Front view



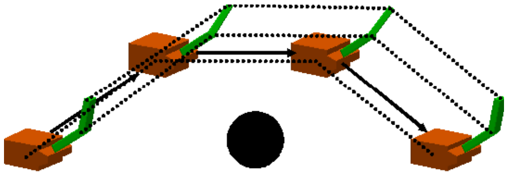
(c) View from over the floor

Fig. 10. The elastic force between the end effectors is much stronger so that the end effector motion is not affected by the repulsive force from other robots. The end effector moves straight while the base of the Bullwinkle avoids the Nomad Super Scout. The figures (a), (b), and (c) represent the same motion viewed from other view point.

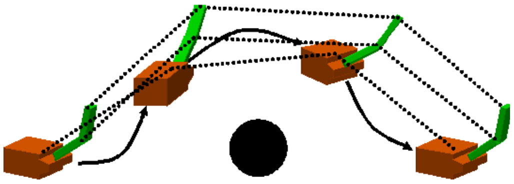
cation, the path shows a little oscillatory motion compared with the path on Fig. 8.

One of the extensions of the elastic force method is control of the end effector motion through a straight path while the base of the mobile manipulator avoids other robots. It is explained in section 2.3, and Fig. 10 shows an example. The end effector of the Bullwinkle moves straight while the base avoids the robot Nomad Super Scout. The coefficient of the elastic force corresponding to the end effector is set as high as five hundred times of those corresponding to other control points.

Fig. 11 explains the need for separate application of the method to the mobile base and manipulator. In case of a robot with nonholonomic mobile base, which is the case for our application, it is not possible to apply the method to the whole robot in its entirety. Even if the method can find a trajectory of the robot through unified application, the base cannot follow through the path generated by elastic force and potential field force because the base is nonholonomic. Thus, the manipulator does not move through the planned path because the manipulator is attached to the mobile base. Therefore, to remove the problem, we cannot help applying the method to the base and manipulator in parts. As a result, the method does not make sense if it is not applied separately to the nonholonomic base and manipulator, because the robot cannot trace the planned path. It should be noted that the task-consistent motion is not possible if the method is applied separately to parts of a robot.



(a) If the mobile manipulator has holonomic mobile base, the base can follow the planned path.



(b) If the mobile base is nonholonomic, the base cannot follow the planned path because the orientation and position are dependent on each other.

Fig. 11. It is required to apply the method separately to the base and manipulator if a mobile manipulator has nonholonomic mobile base. (b) shows the problem of applying the method in its entirety. Since the nonholonomic base cannot follow its planned trajectory, the manipulator moves unpredictably.

Though each of the base and the manipulator moves independently enroute to its goal configuration, it ends up at the specified goal configuration defined on the mobile manipulator as a whole. In this case, we are free to choose a method for collision-free motion of the base. So, the base can avoid collision by using some other methods such as the curvature based method [6, 7], potential field based method [3-5], or elastic band method [14] while the manipulator moves under the control of the proposed approach.

6. Conclusions

A method for multiple robots to coordinate their motion with no collision is proposed. The method assigns motion priority to each robot, and applies the elastic force and potential field force for collision avoidance. The method has the following features.

The method allows the robots to move toward their goal poses without collision. Especially, it results in smooth and efficient collision free trajectory for a mobile manipulator as well as a mobile base.

By adjusting the coefficient for elastic force, it is possible to control the end effector of a mobile manipulator in agreement with a given task requirement, while avoiding other robots.

Though it uses potential field force for repulsion from other robots, it also uses elastic force to keep in the robot's shape. Therefore, the way poses restore their poses and result in smooth and efficient trajectory toward the goal pose when other robots move away.

The approach allows real-time application even for multiple robots of different types because it only requires calculation of elastic force and potential field force.

Applying the method separately to the mobile base and to the manipulator reduces the complexity due to high dimensionality of the mobile manipulator. In addition, another approach can be used for collision avoidance of the mobile base regardless of the method used for the manipulator. The mobile base can be controlled by a method which deals with the nonholonomity of the mobile base while the other part of the robot is controlled by the proposed method.

The paper describes a method which has improved performance over existing elastic force based methods. Also, it shows an extended application of the method to motion coordination of the multiple heterogeneous robots. For improved results, it is desirable to set an optimum priority for each robot motion depending on the assigned task of each robot.

Acknowledgment

This study was supported by research funds from Chosun University, 2006

References

[1] K. Ohara, et al., System design for ubiquitous robotics with functions, *Proceedings of the 2nd International Conference on Ubiquitous Robots and Ambient Intelligence*, Nov. (2005), 66-70.

[2] B. K. Kim, et al., Design of ubiquitous functions for networked robots in the informative spaces, *Proceedings of the 2nd International Conference on Ubiquitous Robots and Ambient Intelligence*, Nov. (2005), 71-76.

[3] O. Khatib, Real-time obstacle avoidance for manipulators and mobile robots, *The Int. J. Robotics Research*, Spring (1986), 5 (1) 90-98.

[4] J. Borenstein and Y. Koren, The vector field histogram-fast obstacle avoidance for mobile robots, *IEEE Transaction on Robotics Automation*, June, 7 (3) (1991) 278-288.

[5] P. Batavia and I. Nourbakhsh, Path planning for the cye personal robot, *Proc. International Conference in Intelligent Robots and Systems (IROS 2000)*, Oct., 1 (2000) 15-20.

[6] N. Y. Ko, R. Simmons and K. S. Kim, A lane based avoidance method for mobile robot navigation, *KSME International Journal*, Nov., 17 (11) (2003) 1693-1731.

[7] R. Simmons, The curvature-velocity method for local obstacle avoidance, *IEEE International Conference on Robotics and Automation*, Minneapolis MN, April (1996) 3375-3382.

[8] D. Fox, W. Burgard and S. Thrun, The dynamicwindows approach to collision avoidance, *IEEE Robotics and automation magazine*, March, IEEE 4 (1) (1997) 23-33.

[9] R. Siegwart et al., Robox at expo.02: a large scale installation of personal robots, *Journal of Robotics and Autonomous Systems*, March, 42 (3) (2003) 203-222.

[10] O. Brock and O. Khatib, Elastic strips: A framework for motion generation in human environments, *The Int. J. of Robotics Research*, Dec. 21 (12) (2002) 1031-1052.

[11] N. Y. Ko, R. Simmons and D. J. Seo, Trajectory modification using elastic force for collision avoidance of a mobile manipulator, *LNAI 4099, PRICAI 2006: Trends in Artificial Intelligence*, Aug. (2006) 190-199.

[12] Simmons, R., et al., Lessons learned from xavier, *IEEE Robotics and Automation Magazine*, June, 7 (2) (2000) 33-39.

[13] B. Sellner, F. W. Heger, L. M. Hiatt, R. Simmons and S. Singh, Coordinated multi-agent teams and sliding autonomy for large-scale assembly, *Proceedings of the IEEE, special issue on multi-agent systems*, July, 94 (7) (2006) 1425-1444.

[14] S. Quinlan and O. Khatib, Elastic bands: Connecting path planning and control, *Proc. 1993 IEEE Int. Conf. on Robotics and Automation*, 2. (1993) 802-807.

Nak Yong Ko received the B.S. degree, M.S. degree, and Ph.D. degree from the Department of Control and Instrumentation Engineering, Seoul National University, Korea, in the field of robotics. He is Professor of the department of Control, Instru-mentation, and Robot Engineering, Chosun University, Korea, from 1992. During 1996~1997 and 2004~2005, he worked as a visiting research scientist at the Robotics Institute of Carnegie Mellon University. His research interests include autonomous motion of mobile robots(collision avoidance, localization, map building, navigation, and planning), manipulator force/torque control, and incorporation of mobile robot technology into GIS.

Dong Jin Seo is a Research Engineer in Robotics Institute at REDONE Tech. He earned B.A degree, M.S. degree and Ph.D. degree from the Department of Control and Instrumentation Engineering, Chosun Uni-versity, Korea in 2000, 2002 and 2006. During 2004~2005, he worked as a visiting student scholar at the Robotics Institute of Carnegie Mellon University, USA. His research interests are multi-robot cooperation, localization, navigation and modeling robot simulation systems with uncertainty.

Reid Gordon Simmons is a research scientist in the department of com-puter science and robotics institute at Carnegie Mellon University, USA. He earned his B.A degree in 1979 in computer science from SUNY at Buffalo, and his M.S and Ph.D. degrees from MIT in 1983 and 1988, respectively, in the field of artificial intelligence. His research interests focus on developing reliable, highly autonomous systems(especially mobile robots) that operate in rich, uncertain environments. In particular, he is interested in architectures for autonomy the combine deliberative and reactive behavior, reliable execution monitoring and error recovery, multi-robot coordination, probabilistic and symbolic planning, formal verification of autonomous systems, and human-robot social interaction.