Combination Control of Remote Operation with Autonomous Behavior in Human-Friendly Mobile Robot

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Abstract

This paper examines the control method in which remote operation is combined with autonomous behavior with the aim to apply to remote operation of mobile robot which moves in human-coexisting environment. Revolution, following, and slowdown are proposed as a concrete technique of combination control, and mounting methods are examined. Simulation system which has been developed in order to examine the effectiveness of proposed technique of combination control is described. This system is programmed on Windows-PC using Visual C++, OpenGL, and DirectX. Mobile robot with autonomous action is remotely operated in this virtual space using joystick. Verification experiment has been carried out and maneuverability and effectiveness of combination control technique has been verified. In revolution technique, robot can turn autonomously when coming into contact with obstacle, but it takes a long time and mileage becomes long to pass through a maze. In following technique, high speed is maintained and transit time is short. In slowdown technique, robot could avoid contact with obstacles completely.

1. Introduction

This paper examines the control method in which remote operation is combined with autonomous behavior with the aim to apply to remote operation of mobile robot which moves in human-coexisting environment.

There are roughly two types on motion control for mobile robot.

1) Autonomous behavior: Mobile robot with autonomous behavior can move, judging on situation and determining action on the spot using information given beforehand such as environmental map and processing information sequentially obtained from external sensors and internal sensors. Autonomous mobile robot can act quickly, since action is determined at that instant by itself and there is no communication time delay compared with a robot which moves receiving instructions from remote operator. However, robot cannot cope with not-assumed situation and environment which changes violently, because usable sensor is restricted and ability of each sensor is limited.

2) Remote Operation: Human operator moves a remote-operated robot from distant place. Remote-operated robot can cope with various situations and its flexibility is high, since ability of human judgment can be used either when robot is operated directly on motion level or when command on operation level or task level is transmitted. However, human operator has to judge by limited information which robot can measure, and mistake on judgment and/or operation will cause trouble on robot directly.

There are strong points and weak points both on autonomous behavior and on remote operation, respectively. So technique of combination control is examined in which both strong points are harvested effectively and each fault is compensated well [1]. The basic idea of such combination technique is well known as "supervisory control". Sheridan categorized the supervisory control into two strict forms; traded control and shared control [2]. We focus on concrete technique in "computer control" on shared control for human-friendly mobile robot which is also under "operator control".

This paper is constituted as follows. First, revolution, following, and slowdown operations are proposed as a concrete technique of combination control, and mounting methods are examined. Next, simulation system developed in order to examine the effectiveness of proposed technique of combination control is described. This system is programmed on Windows-PC using Visual C++, OpenGL and DirectX. Mobile robot with autonomous action is remotely operated in this virtual space using joystick. Verification experiment has been carried out and maneuverability and effectiveness of combination control technique are examined.

2. Combination Control

Control technique in which remote operation is combined with autonomous behavior with priority on remote operation is examined concretely.

2.1. Basic Idea

On conventional combination control, remote operation and autonomous behavior are switched over simply. For example, usual work may be performed on remote operation. And pre-decided easy action and simple pattern of operation such as going back to an initial position are performed autonomously in order to mitigate an operator's burden.

It is considered to combine remote operation of robot with behavior by local autonomous judgment positively. When priority is fundamentally given to operator's operation, target task is executed continuously and safety is secured even if there are a mistake and an oversight of operator. Combination control also deals with problem on communication time delay, because the amount of information can be reduced on remote operation so that a robot locally may process autonomously the information which cannot be transmitted to an operator and the information which does not need to be transmitted.

Mobile robot can avoid contact with obstacles under a technique of combination control (Fig. 1). Mobile robot approaches a wall too much while operator operates the robot remotely, and proximity sensor carried in robot detects the state. Then the instructions from operator which brings the mobile robot closer to the wall are disregarded. The robot can follow the obstacle and it can continue to move. Simultaneously, the information that robot is not moving as instructions and the risk of approaching a wall too much are told to an operator, for example, by displaying on a monitor screen.

Moreover by combination control, mobile robot can avoid a collision (Fig. 2). Range of vision from camera which a mobile robot is equipped with is restricted for remote operation. Remote operation cannot be coped immediately with human being who jumps out of a dead angle. Mobile robot should avoid crashing by stepping aside in a safety area autonomously with processing sensory information locally and disregarding instructions from an operator temporarily, when distance sensor detects an object which approaches quickly. Then robot returns to the original orbit and this dealing action is explained to the operator after checking safety.

In this paper, control method which combines autonomous behavior to assist remote operation using simple sensor as much as possible and using information as few as possible is examined. And technique to use only information obtained from sensor carried in the robot instead of using map given beforehand is examined. That is, the effective control method not only in known environment but also in places visited for the first time is examined. Specifically, action control is examined which is only using information on distance sensor set up around mobile robot in general which is remotely operated its translation and revolution by fore/back and twisting operation of joystick. Here it is discussed that a mobile robot is equipped with two kinds of distance sensor, short range and long range, which measures different range and different resolution, and the discussion is applicable to a mobile robot with only one kind of sensor similarly.

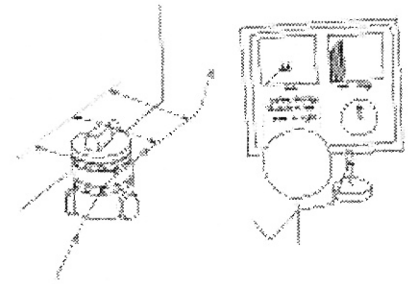


Fig. 1 Contact avoidance

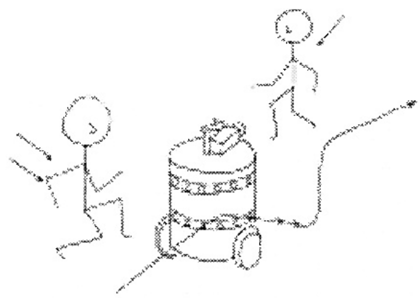


Fig. 2 Collision avoidance

2.2. Revolution

Autonomous revolution is considered such that robot turns around toward open space autonomously when it comes into contact with a forward obstacle. Fundamentally, robot should turn to the left when it touches on right side, and it should turn to the right when touching on left side. The contact with an obstacle for robot means not only the physical contact but also the approaching within a certain distance. Following two methods to detect open space are examined.

1) Comparison of sensory information beginning from the front: RV-1: Open space is determined as longer distance to an obstacle when data from two short-range sensors next to the front are compared (Fig. 3). When there is nothing in the range to measure, or one data is equal to the other, the data from further outside sensors are compared. Comparison will be repeated until the sensors on just right and just left, if there is no difference on data. Robot is revolved at the speed in proportion to the amount of forward instruction as inclination of joystick at that time. Maximum speed of autonomous revolution is set to the same as the direct operation by joystick: for example, it is set to 40 [deg/s]. After some autonomous revolution on the spot, when the robot doesn't touch with any obstacle at its front half, robot can move forward according to instructions by joystick. Robot can deal with forward obstacles by this method since open space is looked for from the front of robot. However, robot may fall into an endless loop which repeats revolution to either side when it comes into a dead end, such as a corner.

2) Comparison of sensory information both on right and left: RV-2: Open space is determined as longer distance to an obstacle when data from two short-distance sensors both on just right and just left are compared in order to recognize and judge with a wide view (Fig. 4). When there is nothing in the range to measure for short-distance sensors, the data from long-distance sensors are compared. Robot may hardly fall into an endless loop even in complicated environment like a maze since the spatial margin in the direction to which robot should turn is compared directly. However at dead ends, such as a corner of room, robot may not necessarily turn to as an operator anticipates, so he/she may not seem to fit in.

2.3. Following

Autonomous following is considered such that robot is translated parallel along an obstacle without changing its direction when it comes into contact with an obstacle in order to become more intuitive and intelligible for human being (Fig. 5). Autonomous revolution has a big advantage that an obstacle can be avoided and movement can be continued. However an operator sometimes loses his/her way since direction of motion of robot is greatly changed compulsorily after contact and revolution.

+) Assumption of tangent direction to the wall using distance sensor: FL: Following is considered that a robot can be translated along the wall by moving in the tangent direction to the wall which can be assumed from the contact position of the robot. First, open space is specified as either in right or in left by the same way as RV-2. When it still cannot specify open space, the same way as RV-1 is used. Virtual front of robot is settled as the normal direction towards open space to the sensor which indicates contact with an obstacle. Robot can move forward in the direction of virtual front because there is no contact at the front half around the robot. Then robot will be translated in the direction of virtual front at the speed in proportion to the tilt of joystick at that time which indicates instructions to move forward. Maximum speed is set to the same as the direct operation by joystick: for example, it is set to 1.2 [m/s]. Sometimes two or more

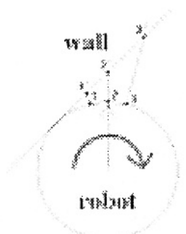


Fig. 3 RV-1

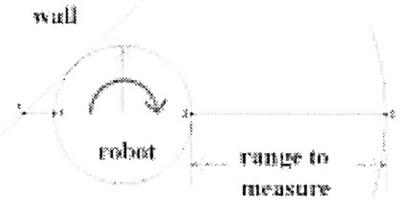


Fig. 4 RV-2

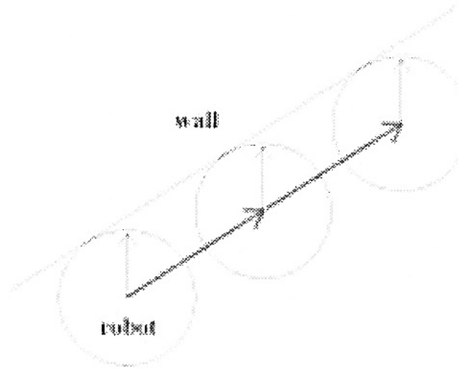


Fig. 5 FL

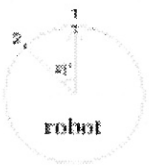


Fig. 6 SD-1

Fig. 7 SD-2

sensors detect contact simultaneously because of the resolution and the scanning cycle time of sensors. However comparatively smooth motion can be achieved by adjusting the relation between control cycle and motion speed even if the direction of motion of robot is not necessarily completely normal to the wall.

2.4. Slowdown

Autonomous slowdown is considered such that robot is restricted on speed of motion, according to the distance to an obstacle. Autonomous revolution and autonomous following are performed when robot touches with obstacle or it approaches into a certain distance. However operation at risk should be restricted before a robot comes into contact with an obstacle. Effective action which a robot is going to leave from an obstacle is also restricted if action is controlled based on data from all sensors arranged around a robot. Following two methods to choose sensor to be used are examined.

1) Front and diagonal front: SD-1: Diagonal front sensor to respond with the twist of joystick by which operator operates revolution is used with front sensor. Inner side of curve should be watched since robot makes a tight turn when joystick is twisted large. For example, the sensor in left side of 45 [deg] is used when joystick is twisted at 50% to the left (Fig. 6), and the sensor in just left is used when joystick is twisted to the maximum. Speed of motion of robot is restricted, say, when the distance between a robot and an obstacle becomes within 2.0 [m] which is the range to measure of short-distance sensor. Maximum speed is decreased gradually in proportion to the distance between a robot and an obstacle. Robot stops for safety when the distance between a robot and an obstacle, for example, becomes shorter than 0.4 [m] which is 1/5 of the range to measure of sensor. Robot can avoid forward obstacle almost certainly. However robot may touch an obstacle on outside of curve which is not taken care of.

2) Front half or rear half: SD-2: All sensors in front half are used when robot moves forward, and all sensors in rear half are used when retreating (Fig. 7). Maximum speed is restricted only when robot approaches an obstacle. And such function shouldn't work when leaving an obstacle in order to satisfy both the maneuverability for operator and the safety to avoid contact certainly in direction of motion. Thereby, a robot and an obstacle do not touch completely. However, robot's speed is restricted when robot runs in parallel along a long wall if the distance to the wall is shorter than the range to measure of distance sensor.

3. Simulation System

Simulation system is built as a platform to examine the techniques of combination control proposed in previous chapter.

3.1. Virtual Environment

OpenGL is used to develop the virtual environment to become easy to be transferred into other models, such as UNIX. Size of robot and obstacle is decided such that 100 units on OpenGL coordinate system are equivalent to 1 [m] in actual world. Field of 2200x2200 in OpenGL coordinate system is prepared and it is enclosed with wall of 100 (1 [m]) in width. So virtual environment is built in the area of 2000x2000 (20x20 [m]), and passages and obstacles are stored in two-dimensional matrix as 0 and 1. Robot moves in this virtual environment. Height of ceiling is 200 (2 [m]) and the object like a fan is regularly hung and is rotated to make presence in depth. Robot is expressed as a blue cylinder with 0.4 [m] in diameter and 0.8 [m] in height, modeling a non-holonomic type mobile robots Nomad 200 made by Nomadic Technologies Inc. Red arrow which indicates the front of the robot is displayed on upper surface of virtual robot.

3.2. Operation of Robot

Robot is operated using four-button joystick with throttle, rudder and hat switch. Rudder is to operate direction of the object in flight simulation and it is usually a pedal type. Here, twisting joystick is substituted for rudder operation. Program is developed using Direct Input of DirectX 7.0a in order to acquire the state of joystick at high speed.

Robot is translated forward and backward when joystick is tilted. Robot is revolved right and left when joystick is twisted. Speed of motion is set in proportion to degree of tilt angle or twist angle of joystick, and the maximum is settled as 1.2 [m/s] and 40 [deg/s], respectively.

3.3. Sensor and Display

Robot may acquire distance information from the distance sensor as information on external world. In this simulation long-distance sensor (range to measure: 10 [m], resolution: 1/100) and short-distance sensor (range to measure: 2.0 [m], resolution: 1/100) are arranged around the robot in order to obtain position and distance of surrounding obstacles, referring Nomad 200. Number of each sensor is 32 in simulation, even though Nomad 200 has 16 sensors. On a software simulation sensor acquires external-world information by referring to two-dimensional matrix in which virtual environment is stored.

Information obtained from long-distance sensor and short-distance sensor is represented on operation screen in left and right at the bottom as translucent sensor frame, respectively. Sectors which show the range to measure of a sensor are displayed around robot. Sectors are become short according to the distance when detecting an obstacle. Sectors are displayed in green and yellow for long-distance sensor and short-distance sensor, respectively. Information on short-distance sensor is overlapped on information on long-distance sensor to specify each range to measure. Form of obstacle in two-dimensional plane also can be displayed by lining the end of the sectors. Two-dimensional rough map around the robot can be shown on the screen even if the robot doesn't have a map beforehand.

Contact of robot with obstacle means obstacle is detected within distance set up beforehand in short-distance sensor. Operator can become aware of contact by changing color from blue to red on robot shown in the center of the sensor frame. Instructions from joystick are ignored in forward translation at this time. Robot can get away from contact condition when there is no contact with an obstacle at the front half around the robot by leaving the obstacle or revolving on the spot.

3.4. Operating Environment

The operating environment of the built system is as follows, CPU: Pentium III 450MHz, Video: Viper V770 (Riva TNT2), Memory: 128MB SDRAM (PC100), and Joystick: Microsoft Side Winder Force Feedback Pro. In this operating environment, system is operated comfortably in 20 [frame/s] without frame omission, although freezing occurs frequently in 30 [frame/s].

4. Verification Experiment

Technique of combination control of remote operation with autonomous behavior examined in Chapter 2 is applies to the simulation system shown in Chapter 3 in order to confirm features of each combination control technique and to verify its functions. Each combination control is performed exclusively in order to verify the effect of each technique.

4.1. Experimental Setup

A maze is built within the area of 14x12 [m] in virtual environment, and start area and goal area are set at both ends. Operator operates a joystick and moves a robot watching the picture from main camera installed on upper surface of the robot on operation screen. Height of wall is set to 0.5 [m] from the ground which is lower than height of camera as 0.9 [m] in order to improve operator's prospect under operation. (Fig. 8)

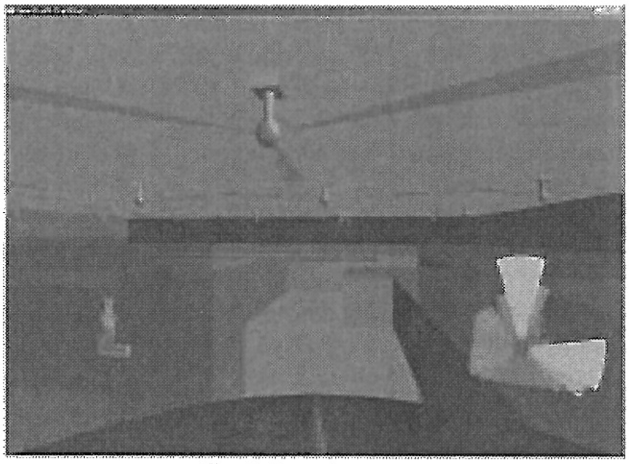


Fig. 8 Operation screen

4.2. Experimental Results

Subject is a male in his late twenties. Locus of mobile robot and number of times of collision with wall are recorded. Transit time, mileage, and mean speed are calculated. Operation is tried in three times in each case of no combination, RV-1, RV-2, FL, SD-1, and SD-2. The average number in each case is shown in Table 1.

1) Display of sensory information: It improves maneuverability of robot to display information on distance sensors translucently on operation screen. Two-dimensional rough map obtained from sensory information becomes a preliminary-announcement and display for operator about the area where a robot is going to move. Transit time is short and variation of path in trial decreases by displaying sensory information.

2) Technique on revolution: Transit time become shorter in RV-2 rather than RV-1. In RV-1 robot may often fall into endless loop which repeats revolution to either side at a corner. Operator has to operate to overcome the situation positively. In RV-2, robot can continue to move forward without falling into endless loop, even though sometimes robot is not revolved as operator wishes. Then RV-2 is considered to be the representative technique on autonomous revolution.

3) Technique on slowdown: Contact with an obstacle is not completely avoidable in SD-1. Contact may be avoided on inside of curve and contact often occured on outside of curve. SD-2 is effective in order to avoid contact certainly even if speed of motion becomes lower. Then SD-2 is seems to be the representative technique on autonomous slowdown.

4) Feature of three combination techniques: Locus of robot in three trials on no combination, RV-2, FL, and SD-2 are shown in Fig. 9, respectively. Transit time becomes long without combination control. It is because it takes long time to operate robot in detail such that the robot has to move backward and the direction of motion must be changed when touching with an obstacle. Number of times of collision decreases compared with that on combination control of revolution or following. It is because robot is operated carefully in order to avoid complicated operation after contact.

It takes long time and mileage becomes long with revolution technique because speed of translation becomes zero during revolution when touching with an obstacle. Furthermore robot will meet and move outside the curve on passage when operator uses autonomous revolution positively almost without operating direction of

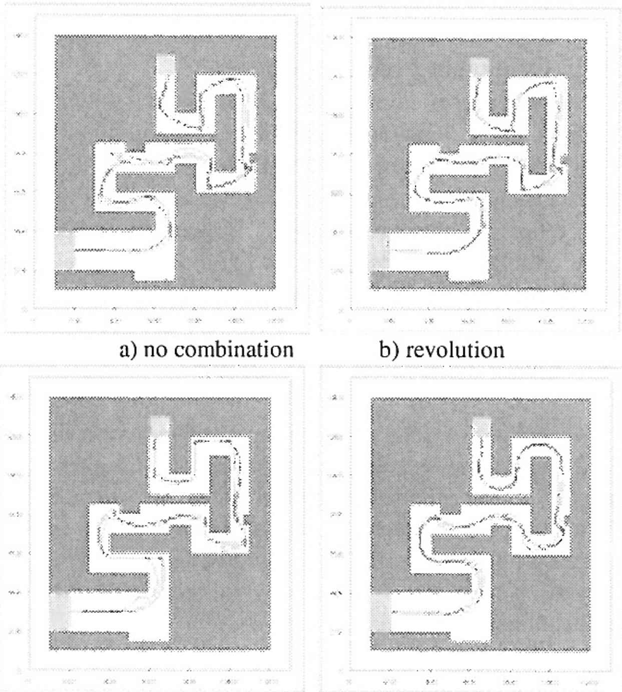
Table 1. Experimental Results

Combination control	Transit s	Mileage m	Speed m/s	Collision num.
No	44.78	34.96	0.78	12.33
RV-1	45.10	36.27	0.80	14.33
RV-2	37.88	33.03	0.87	11.33
FL	31.93	32.66	1.02	10.33
SD-1	43.82	31.95	0.73	3.67
SD-2	59.15	31.07	0.53	0

robot. Mileage becomes the longest for this reason.

In following technique robot can move forward continuously without stopping on the spot even when touching with an obstacle. Speed can be maintained comparatively high during start to goal, and mean speed is also the highest.

Robot can avoid contact with a wall completely in slowdown technique although transit time becomes long. Moreover mileage is comparatively short in a smooth path. Robot can pass through a corner with comparatively small radius because autonomous slowdown works well in curve.



a) no combination b) revolution

c) following d) slowdown

Fig. 9 Locus of mobile robot

5. Conclusion

5.1. Summary

This paper examined the control method in which remote operation is combined with autonomous behavior with the aim to apply to remote operation of mobile robot which moves in human-coexisting environment.

Autonomous revolution is considered such that robot turns around to open space autonomously when it comes into contact with a fore obstacle. Autonomous following is considered such that robot is translated parallel along an obstacle without changing its direction. Autonomous slowdown is considered such that robot is restricted on speed of motion according to the distance to an obstacle. And mounting methods were examined concretely.

Simulation system was developed as a platform to verify the effectiveness of the proposed technique of combination control, which is programmed on Windows-PC using Visual C++, OpenGL, and DirectX. Mobile robot with autonomous action is remotely operated in this virtual space using joystick. Verification experiment has been carried out and features of each combination control technique have been clarified.

It takes long time and mileage becomes long with revolution technique because speed of translation becomes zero during revolution when touching with an obstacle. In following technique robot can move forward continuously even when touching with an obstacle, then speed can be maintained comparatively high and transit time becomes short. Robot can avoid contact with an obstacle completely in slowdown technique although transit time becomes long.

5.2. Future Works

Each combination control was operated exclusively in the experiment in order to verify the effect of each technique. Both revolution and following shown here should be performed with slowdown technique simultaneously since robot which moves in domestic environment must not come into contact with neither human beings nor obstacles. Development of algorithm which arranges these autonomous techniques according to situation is a future subject and it should be applied to mobile robot efficiently.

Moreover, human being cannot finish processing information only with visual information, although picture information from camera and distance information from distance sensor which a robot can acquire were visually shown on operation screen in the experiment. Other sense such as tactile sense by force feedback and acoustics by Direct Sound of DirectX should be examined in order to transmit situation around robot more exactly and intelligibly.

Acknowledgment

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