



Location-aware robot, and system for controlling such a robot

Related Applications

- 5 The present application is related to Singapore patent application no. 200504866-5, filed 12 July 2005, by Sun Xiaobing, Xu Jin, Ma Yugang and Kanzo Okada, three of whom are inventors also for the present application.

Field of the invention

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The present invention relates to tracking the position of moving robots, and also to controlling them.

Background of the invention

- 15 A robot is a machine which moves itself. For many applications, the movement is within a certain area where multiple obstacles exist, e.g. a house, an office or a warehouse etc. To avoid collisions between the robot and the surrounding objects, the robot needs know its position relative to the surroundings. The traditional ways for positioning a robot include using ultrasonic transducers, a
20 video camera or an infrared scanner etc. These positioning methods have one or more of the following disadvantages: low accuracy, complex implementation, large size, and/or high cost.

- In recent years, positioning using a wireless network has been proposed [2], [3], [4]. In these systems, the position of a robot can be determined by using
25 time-of-arrival (TOA) or/and direction-of-arrival (DOA) of wireless signals at least two base stations. Ultra-wideband (UWB) impulse radio based positioning systems are preferred for indoor positioning applications due to their unique features of penetrating walls and avoiding multi-path signals. A typical prior art UWB indoor positioning system, of the kind shown in [2], is illustrated in Figure 1.
30 Multiple anchor points (four are shown, marked from "Reference Radio R1" to "Reference Radio R4") are needed to locate the positions of the moving robots



(shown as "Robot M1" and "Robot M2"): Before the positioning, it is necessary to know the positions of the reference radios. These radios also need to be synchronized and connected to a central control station. The preparation required to do this is time consuming and expensive, and in some cases may not even be compatible with the operating requirements of the environment. Furthermore, it is not convenient to have to repeat this process for each new environment, not least because usually professional knowledge is required.

Summary of the Invention

This invention aims to provide a new way to locate a robot's position, and optionally also control its movement.

In general terms, the invention proposes in a first aspect, that UWB pulses are transmitted in both directions between a base station and at least one robot, the base station being capable of using the UWB pulses it receives to obtain both the direction and distance of the robot from the base station, and to use the UWB pulses it sends to the robot to transmit data to the robot, the robot moving in response to the data. Optionally, the robot can also send data to the base station.

Since only a single base station is required (although in certain embodiments multiple base stations may be provided to increase positioning accuracy and enlarge the positioning area), the cost of the system may be relatively low. Furthermore, it may be capable of being deployed in a new environment at relatively low cost.

If the base station has access to a map of the environment in which the robot moves, the base station can determine the position of the robot relative to the surrounding objects. Therefore a movement path for the robot can be determined. The base station can either use the communication link to send position information to the robot for it to calculate itself the movements it should make, or the base station can directly calculate the control parameters and send this information to the robot for it to simply execute. In the latter case, the robot

can be simply a moving machine and the control function can be provided by the base station.

The motion state parameters of the robot can also be sent back from the robot to the base station for it to calculate the control parameters for the robot.

- 5 The base station will track the robot continuously. One or more robots can be tracked by a single base station. The base station may send and/or receive signals to/from the respective robots sequentially.

The (or each) robot may be an entertainment robot which interacts with one or more people, or a gaming robot which moves to play a game with people
10 or with another gaming robot, or a service robot which take care of older people or children, or a vacuum cleaning robot which automatically cleans a house.

The direction and distance of the robot from the base station may be obtained using the mono-station UWB positioning and communication system proposed in [1]. This UWB system can provide a high accuracy positioning (in cm
15 order) as well as a bi-directional communication link.

A second aspect of the invention proposes that a robot includes a first UWB tag, and an object to be a handled by the robot contains a second UWB tag. A base station receives UWB signals from both the UWB tags, and determines the direction and range of both of the tags, and thereby generates
20 information according to which the robot moves to manipulate the object.

As in the first aspect of the invention, the second aspect gives the advantages of requiring only a single base station (though multiple base stations may optionally be used), leading to reduced cost and easier set-up.

In a first case, the robot moves independently from the UWB station, and
25 the base station passes the information (which may be position information and/or control information) to the robot. This is then a special case of the first aspect of the invention discussed above.

In a second case, the robot includes at least one tool, the first UWB tag being mounted on the tool. In this case, the base station may be mounted on the
30 robot, and the purpose of the first UWB tag is to permit the base station to

generate information in response to which the tool moves relative to other parts of the robot.

Either aspect of the invention can be expressed either as a system including at least one base station and at least one robot, or as a method of
5 moving at least one robot employing at least one base station.

Brief description of the drawings

An embodiment of the invention will now be described for the sake of example only with reference to the following drawings, in which:

10 Figure 1 shows schematically a known robot positioning system employing at least two UWB anchor points.

Figure 2 shows a first embodiment of the present invention to control the movements of robots in an indoor environment.

15 Figure 3 illustrates how the first embodiment controls more than one robot using a time share protocol.

Figure 4 is a flow diagram of the steps carried out in by the first embodiment by the base station, to control a robot moving to a desired place or along a specific path.

20 Figure 5 illustrates how the first embodiment controls a robot to recharge itself when its battery power is low.

Figure 6 illustrates how a second embodiment of the invention controls the hand movement of a robot to move a object to a desired place

Detailed description of the embodiments

25 Ref. [1] proposed a mono-station positioning method that can determine the position (range and direction) of a UWB tag using only one base station. That document did not disclose that the UWB tag might be associated with a robot. The UWB tag included an omni-directional antenna, while the base station included an antenna assembly with a plurality of directional antennas with their
30 main beam directions non-parallel (specifically, two directional antennas with their main beam directions spaced apart by a pre-determined angle). The base

station performed both time-of-arrival (TOA) estimation using straightforward echo delay measurement, and direction-of-arrival (DOA) by comparing the relative amplitudes of the UWB pulses received by the two antennas. The two estimations can be implemented using a compact antennae array structure and high accuracy DOA can be achieved. Using both the TOA and the DOA information, the position of the UWB tag relative to the base station can be determined.

The basic idea for UWB based robot positioning and control system is illustrated in Figure 2. Two robots 1,2 are controlled from a single base station 3 having an antenna structure 4 (which may be the compact antenna array structure of [1]). The base station 3 sends UWB pulses to the robots 1, 2, and measures echo signals transmitted back by the robots 1, 2, each of which has a UWB communication device for receiving and transmitting UWB pulses using an omni-directional antenna. The base station 3 finds the respective distances ("ranging") and directions of the robots 1,2, and controls the robots 1, 2 to move in a living-room environment including a desk 4, a sofa 5 and even a wall 7.

Bi-directional communication exists between the base station 3 and the robots 1,2. This can be implemented at the same time as the ranging. The data can be sent from base station 3 to the robots 1, 2 by modulating the group of the pulses used for ranging, or use a dedicated time slot to send a group of pulses for communication only. In similar way, the data can be sent from the robots 1, 2 to the base station 3 by either modulating the echo back pulses used for ranging, or using another dedicated time slot to send another group of pulses for communication only. The modulation schemes used in the UWB signals can be the conventional BPSK, PPM or spreading code etc.

The pulses which the base station 3 sends to the robots 1, 2, includes packets of pulse groups. Some or all packets may include one or more synchronization pulse group, ID pulse group, ranging pulse group, direction-finding pulses group, and/or pulse groups for any other purpose, such as command data. Based on the packet information exchange, the position of the robot 1, 2, can be determined and communication data can be exchanged

between them. The positioning information and the communication data can be used to control the robot.

One or more robots 1,2 can be controlled by a single base station. If there is more than one robot, the base station 3 will detect and communicate with them one after another sequentially. This situation is illustrated in Figure 3. Each robot will have a respective ID. In the beginning, a robot (say, robot 1) just waits and listens to pulses generated by the base station, and determines the ID within each packet.

During time period 1, the base station 3 sends out pulses including the ID of robot 1. The robot 2, recognizes this, and remains in the waiting state. The robot 1, however, recognizes its ID, and starts working by reflecting the incoming ranging pulses, sending a group of pulses for the base station to use to find the DOA of the pulses, and/or modulating a group of pulses for communication. At the same time, the robot 1 will demodulate the incoming pulses to extract any other information they may contain. After exchanging a full packet with the base station, the robot 1 will return to the listening state again and wait for the next call from the base station. Similarly, in period 2 the base station 3 communicates only with the robot 2, and in period 3 the base station communicates once more with the robot 1. Of course, the number of robots (and IDs) is not limited to two.

Based on the above description, it can be seen that a single base station 3 can detect the respective positions of one or a group of robots 1,2 and communicate with them at the same time. Therefore, many functions can be enabled for the robots by making use of this feature.

In one scenario, the base station 3 is used to guide a robot 1,2 to move to a desired target position. By detecting the position of the robot 1,2 in real-time, the base station 3 can tell the robot where to go in its next step. The information data about the next step movement can be sent to the robot 1,2 from the base station using the communication link. After receiving the information, the robot 1,2 can move accordingly. The base station 3 will continue detect the position of the robot 1,2 after the movement and use it as the feedback information to determine the following movement steps. This loop will be continued until the

desired position is reached. In another situation, the robot 1,2 can send movement state information specifying its present state, such as its speed, acceleration, moving direction (e.g. from its gyroscopes measurements) etc back to the base station 3 using the robot-to-base station communication link. Using this information and the desired next moving position, the base station 3 can directly calculate revised control parameters, such as the acceleration, direction etc, for the robot 1,2 and send these parameters to the robot through the base station-to-robot communication link. After receiving these control parameters, the robot 1,2 can just simply execute them. By this way, the robot 1,2 can be much simplified compared to many current designs, as a machine which is enabled for movement only, rather than additionally to control its own movement. All of its intelligent functions such as sensing processing, control etc can be removed. That will enable a robot 1,2 to be made at very low cost. Using a similar process, with the knowledge of the surrounding map, the base station 3 can guide the robot 1,2 to move along a specific path to avoid the collision with surrounding objects.

A block diagram to implement the above process is illustrated in Figure 4. In this process the base station 3 controls a robot which may be either of the robots 1,2. In step 401, the base station 3 obtains a target position (x_0, y_0) (in a two-dimensional space with orthogonal axes x and y), e.g. by calculating it or reading it from one or more inputs. In step 402, the base station 3 determines the robot's current position. In step 403, the base station 3 determines whether the target position has been reached. If so, in step 404 the method terminates, or returns to step 401 for the base station 3 to obtain a new target position. If not, in step 405 the method obtains movement state information from the robot. In step 406, the base station 3 derives control parameters to control the robot to take a step $(\Delta x, \Delta y)$. In step 407, the robot receives the control parameters and moves accordingly.

One embodiment using the scheme of Fig. 4 is controlling a vacuum cleaning robot. Cleaning robots conventionally have a "brute force" control mechanism, i.e., the robot continues moving along a straight line until it hits an

obstacle. Then, it will change its direction of movement to another non-blocked direction. Since the direction change is random, it is possible that the robot will move to some areas more than once while it will never reach some other areas. This will reduce the efficiency of the cleaning. By using the embodiment,

5 however, if the room layout and the positions of the obstacles are known, the base station 3 can improve the efficiency of the cleaning robot by planning its optimal moving paths and controlling its movement in real-time. As mentioned before, the control parameters can be directly sent to the robot for it to simply execute. Therefore the cleaning robot can be simplified and made at low cost and
10 low weight. The base station can either calculate the optimal paths by itself, or it can be connected to a PC and use software running on the PC to plan the optimal paths.

Another embodiment using the scheme of Fig. 4 is to control the vacuum cleaning robot, or more generally any kind of robot, to recharge itself. Cleaning
15 robots are normally battery powered. Due to the limited energy of the battery, the output power of the cleaning process cannot be very high, since otherwise frequent recharges would be required. If the recharging is done by a human being, it will be troublesome. The scheme of Fig. 4 can be used to avoid such requirement. The arrangement is as shown in Fig. 5. When the power stored in
20 the robot 1 is low, the data packets transmitted by the robot 1 to the base station 3 include information indicating that fact. By knowing the site (x_0, y_0) of the charging site 8, the base station 3 can guide the robot to it around any intervening obstacles 5. When the robot is close enough to a charging site 8, appropriate magnetic mechanisms 9, 10 respectively on the robot and at the
25 charging site, can be used to drag power plugs of the robot (not shown) to meet power plugs (not shown) of the charging site.

The other embodiments may include the following situations: 1) The robot may be a health care robot that is controlled to move a handicapped or elderly person to a desired position. 2) The robot may be an entertainment robot with a
30 TV, PC or speakers mounted within it, and may be moved to a target position in front of a user to allow them to enjoy its contents. 3) The robot may be gaming

robot that moves to play a game such as run-and-catch or football with a user, or indeed there may be a plurality of gaming robots.

Fig. 6 illustrates a further embodiment of the invention, sharing with the earlier embodiments the features of mono-station positioning and two-way communication. In this embodiment, the base station 13 is mounted on a central "body" portion of a robot 11. The base station has an antenna structure 14. The robot 11 includes an arm 15, having a mechanical manipulation device ("hand") 16, including a first UWB tag 17. The arm 15 can be moved relative to the body of the robot 11, and the "hand" 16 can also be opened and closed to grab or release an object. The robot 11 is also preferably capable of translational motion (either controlled by the base station or not). A second UWB tag 19 is located on an object 18, and the base station 13 uses the techniques discussed above to find the position of the object 18 and control the arm 15 to move the object 18 towards a target position 20.

An example of an application of the above scheme is to let the robot complete some jobs in places dangerous to humans. For example, it can be used in a nuclear power generation plant where due to the high radiation, some jobs must be completed by robots.

In another example, the base station 13 is not mounted on the robot 11, but in a fixed location, where it controls the movement of the robot to in turn control the movement of the object.

Note that in applications where a tool (e.g. a hand) is controlled to act on an object, it can be useful for the position of the tags 17, 19 to be performed in three dimensions, not just two. For this purpose the number of antennas in antenna assembly 14 of the or each base station 13 is preferably at least 3, with their respective main beam directions not being co-planar, and being spaced apart by known angles. That will enable measurement of both the horizontal DOA and the elevation DOA. The implementation of 3-D positioning is also disclosed in [1].

Although in the embodiments described above, there is only a single base station 3, 13, the invention is not limited in this respect. An alternative

embodiment includes more than one base station, each of which is individually capable of finding both the direction and distance of one or more tags, mounted for example on respective robots. The base stations may communicate with each other. Additionally, each base station may communicate with each of the robot(s).

5 This scheme can be used to increase the positioning accuracy for the robot(s) since more than one measurement of the position of the robot(s) can be obtained. It can also be used to increase the working area of the system since it is possible that when a robot is in a position where the signal from one base station is weak, the signal from another base station is strong.

10 Although only a few embodiments of the invention have been described here, many variations are possible within the scope of the invention as defined by the present claims, as will be clear to a skilled reader.

References

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[1]. Xiaobing Sun, Jin Xu, Yugang Ma and Kanzo Okada, "Positioning Methods and Systems for UWB Devices", Singapore patent application no. 200504866-5, filed 12 July 2005. The disclosure of this document is hereby incorporated by reference.

20 [2]. Susan J. Glenn and Gregorey A. Shreve "Method and System for Controlling a Robot" U. S. Patent No. 7,069,112 B2, Jun. 27, 2006

[3]. Akira Maeki "Location Aware Automata" U. S. Patent No. 7,170,252 B2, Jan. 30, 2007

[4]. David R. Oran and Silvano Gai "System for Dynamically Tracking the
25 Location of Network Devices to Enable Emergency Services", U. S. Patent No. 1, 149,499 B1, Dec. 12, 2006

Claims

1. A system comprising:
 at least one robot, the or each robot including a first UWB device for
 5 generating and receiving UWB pulses;
 at least one base station, including a second UWB device for generating
 and receiving UWB pulses, and arranged to determine the direction and range of
 the first UWB device, to generate data from the direction and range, and to
 transmit the data to the or each robot;
 10 the robot being arranged to receive the data and to move in response to
 the data.
2. A system according to claim 1 in which communication data is encoded in
 the UWB pulses transmitted by the or each first UWB device, the second UWB
 device being arranged to extract the communication data from the UWB pulses.
- 15 3. A system according to claim 1 or claim 2 in which the base station
 includes an antenna structure including at least two antenna having respective
 main beam directions spaced apart by a predetermined angle, the base station
 determining the direction of the first UWB devices by comparing the relative
 amplitudes of the UWB pulses received by the at least two antennas.
- 20 4. A system according to claim 1, claim 2 or claim 3 in which the data is
 position information specifying the position of the robot, the robot being arranged
 to derive desired movements from the position information, and to implement the
 desired movements.
5. A system according to claim 1, claim 2 or claim 3 in which the data is
 25 control parameters indicating actions to be performed by a transport mechanism
 of the robot, the transport mechanism being arranged to performed the indicated
 actions.
6. A system according to claim 5 in which the control parameters are
 generated using a map of the environment of the robot.
- 30 7. A system according to any preceding claim in which the robot is arranged
 to transmit movement state parameters specifying characteristics of its

movement to the base station, the base station employing the movement state parameters to generate said data.

8. A system according to any preceding claim in which the robot is a vacuum cleaning robot.

5 9. A system according to any preceding claim, arranged to store target position data indicating the position of a charging station, the robot being arranged, upon a low power state being detected, to move to the charging station.

10 10. A system according to any preceding claim, in which the robot includes at least one tool and an actuator for moving the tool relative to the rest of the robot, the first UWB communication device being associated with the tool, and the actuator being arranged to receive said data, whereby said data controls the movement of the tool relative to the rest of the robot.

15 11. A system according to any preceding claim, further including an object associated with an additional device for generating UWB pulses, the base station being operative to detect the distance and direction of the additional device, and thereby generate data for controlling the movement of the robot in relation to the object.

20 12. A system according to any preceding claim including a plurality of said base stations, the base stations being in mutual communication.

13. A system according to any preceding claim in which there are multiple said robots, the or each base station being arranged to communicate with the robots sequentially, the UWB pulses transmitted from the base station including an ID specific to one of the robots.

25 14. A system comprising:

at least one robot, the or each robot including a tool associated with a first UWB device for generating UWB pulses;

an object subject to operation by the robot, the object being associated with a second UWB device for generating UWB pulses;

30 at least one base station, including a third UWB device for receiving the UWB pulses from the first and second UWB devices, determining the direction

and range of the first and second UWB devices, and generating data, the tool being arranged to move in response to the data.

15. A system according to claim 14 in which the base station is mounted on the robot.

5 16. A method of moving a robot including a first UWB communication device for generating and receiving pulses, the method comprising:

the robot generating UWB pulses;

at least one base station receiving the UWB pulses, determining from them the direction and range of the robot, and transmitting data to the robot
10 encoded in UWB pulses;

the robot moving in response to the data.

17. A method according to claim 16 in which:

said step of receiving the UWB pulses includes receiving the pulses using each two antennas having respective main beam directions spaced apart by a
15 predetermined angle, and

said step of determining the direction of the robot comprises comparing the relative amplitudes of the UWB pulses received by the two antennas.

18. A method according to claim 16 or claim 17 in which the data is position information specifying the position of the robot, the robot deriving desired
20 movements from the position information, and implementing the desired movements.

19. A method according to claim 16 or claim 17 in which the data is control parameters indicating actions to be performed by a transport mechanism of the robot, the transport mechanism performing the indicated actions.

25 20. A method according to claim 19 further comprising generating the control parameters using a map of the environment of the robot.

21. A method according to any of claims 16 to 20 in which the robot transmits movement state parameters specifying characteristics of its movement to the base station, the base station employing the movement state parameters in said
30 step of generating said data.

22. A method according to any of claims 16 to 21 in which the robot is a vacuum cleaning robot.

23. A method according to any of claims 16 to 21 further comprising:
detecting a low power state of the robot;

5 the robot moving to a charging station for recharge.

24. A method according to any of claims 16 to 23, the robot including at least one tool and an actuator for moving the tool relative to the rest of the robot, the first UWB communication device being associated with the tool, the method comprising the actuator receiving said data and accordingly moving of the tool
10 relative to the rest of the robot.

25. A method according to any of claims 16 to 24, further including an object associated with an additional device for generating UWB pulses, the base station being operative to detect the distance and direction of the additional device, and thereby generate data for controlling the movement of the robot in relation to the
15 object.

26. A method according to any of claims 16 to 25, in which the step of receiving the UWB pulses is performed by a plurality of said base stations, the base stations being in mutual communication.

27. A method according to any of claims 16 to 26 in which there are multiple
20 said robots, the or each base station communicating with the robots sequentially, the UWB pulses transmitted from the base station including an ID specific to one of the robots.

28. A method of moving an object using the tool of a robot, the tool being associated with a first UWB device for generating UWB pulses, and the object
25 being associated with a second UWB device for generating UWB pulses, the method comprising:

at least one base station receiving the UWB pulses from the first and second UWB devices, determining the direction and range of the first and second UWB devices, generating data and transmitting the data to the tool, and

30 the tool moving in response to the data to act on the object.

29. A method according to claim 28 in which the base station is mounted on the robot.
30. A method according to claim 29 performed in an environment dangerous for humans.