Rule-based system to assist a tele-operator with driving a mobile robot

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***Abstract*— Simple real time AI techniques are presented that support tele-operated mobile robot operators when they are steering. They permit a tele-operator to be included in the steering as much as possible, while offering help when required to avoid obstacles and to reach their target destination. The direction to a destination (via point) becomes an extra input along with the usual inputs from a joystick and an obstacle avoidance sensor system. A recommended direction is suggested and that is mixed with joystick position and angle. A rule-based system provides a suggested angle to turn the robot and that is mixed with input from a joystick to help a tele-operator to steer their mobile robot towards a destination.**

Keywords*— Tele-operation, Mobile robot, Assist, Rule-based, AI, Steering, Collision Avoidance.

I. Introduction

Control methods and structures are described for a tele-operated mobile robot to obtain knowledge about the surroundings while advancing in the direction of a more overall end point. Help is provided to the tele-operator to assist them in avoiding obstructions.

A tele-operater may not be able to steer a mobile robot safely because of limitations. For example, an operator may not be able to see the mobile robot or the environment (perhaps due to smoke) or it may be in a location isolated from the tele-operator. The systems presented here are to help tele-operators drive in those sorts of conditions and circumstances.

Tele-operated mobile robot control systems are often open-loop. Operators designate speed and direction by moving a joystick and the mobile robot tends to go in that direction and at that speed. Operators respond to conflicts (for example an object in the way) and adjust their preferred route. In this research, input from the tele-operator is processed and blended with input from an ultrasonic sensor system and a goal end point in order to assist an operator in guiding the mobile robot. Global and local planning procedures are mixed within a rule-based system to assist the tele-operator.

Global paths are blended with local input from the ultrasonic sensor system [1].

Tele-operated mobile robot navigation has been investigated in the literature [1-4]. The algorithms described have usually been for local planning and they were not improved in a global way. Systems to help tele-operators avoid obstacles has been a desired supplementary attachment for such systems [5] along with systems to suggest movements based on local sensor inputs in unknown and unstructured environments [4].

There has been work with mobile robots to plan initial paths and modify them locally as obstacles are detected [1] but that kind of procedure has rarely been effectively used to help tele-operators. In the techniques and structures described here, a local planning unit produces drive to wheel motors depending on inputs from: a joystick, on-board ultrasonic sensors and a more global target. The tele-operated mobile robot responds rapidly to the human tele-operator and to changes in the environment ahead of the robot to avoid any unexpected obstacles but tends to move towards a target destination whenever possible.

Huq *et al*. described a fuzzy context-dependent blending of schemas [6] that removed some of the limitations of earlier methods and instead used a goal oriented navigation while also evading any obstacle in the path of the robot. Genetic algorithms were mixed with fuzzy logic to resolve local position and mapping problems in [7]. The method searched for an appropriate plan to give local data about the environment. Bennewitz and Burgard presented randomized planning methods that could generate routes in real time in unknown environments without any need for a vision system [1], [8], as well as accurately following a generated trajectory [9]. Hwang and Chang created a related avoidance technique for car-like systems using fuzzy decentralized sliding-mode control [10]. Song and Chen improved the potential field method by solving some problems associated with local minima [5] and Nguyen *et al* described methods using Bayesian Neural Networks for obstacle avoidance [11].

This paper presents a method that partly optimises a minimum-cost route to a target destination. Speed is mostly regulated by the movement of a joystick, but input from a path suggested by simple AI systems [12-15] is also considered. The straightforward and quick reasoning uses perception based rules that are comparable to some presented by Parhi & Singh for an autonomous mobile robot [1].

Algorithms trade distance to obstacles against path length. Rules decide on a recommended steering angle and that is combined input from the joystick to generate the drive signals to the mobile robot motors.

Systems and methods were successfully verified using simulations and then the hardware was mounted onto a Bobcat II mobile robot base (Fig. 1).

Fig. 1 The tele-operated mobile robot being remotely driven along a corridor

Mobile robots need to avoid obstacles [16]. Numerous sensors have been suggested to avoid local obstacles, for example: laser or structured light [17]; ultrasonic [18]; and infra-red [19]. Global systems do not always perform properly inside buildings [20] but more simple local sensors have been successfully used to calculate position: tilt, odometers, gyros, and ultrasonics [21, 22]. Image processing systems can help if there is a clear view from the camera but they require relatively large amounts of processing and have tended to be more complex [23], although they are becoming less and less expensive and computing power is increasing quickly [24]. The human tele-operator is the best source of knowledge about the situation and surroundings but reduced visibility, separation and incomplete or imperfect information about the environment can weaken the abilities of the human operator [25].

Ultrasonics were chosen to detect range because they were straightforward, uncomplicated, inexpensive and tough [26].

Part II of the paper describes the input from the joystick and the sensors and Part III describes the kinematics of the robot base. Part IV considers the control of the mobile robot base and the rules used. Part V discusses the testing and results and the paper ends with some brief conclusion in Part VI.

II. Input from the Joystick and Sensors

A. *The ultrasonics*

The ultrasonics used were like those used in [27, 28]. Ultrasonic sensors were mounted on the front of the mobile robot above the driving wheels. The time for a pulse to send and then be reflected back to the sensor delivered a measure of the distance to obstacles.

The mobile robot had a fibreglass body and substantial steel framework for steadiness, stability and strength. Driving wheels were at the front and trailing casters were at the back. Ultrasonic sensors were fixed to the forward-facing panels above each driving wheel. The mobile robot is described in more detail in [29]. A joystick steered the robot.

The joystick connection with the tele-operated mobile-robot was severed and instead, a computer was added between them to manage input from the joystick. The system could operate in two different modes:

- Joystick input sent directly to the robot controller.
- Computer modifies the direction and speed of the mobile robot using the methods presented here.

The methods used these rules:

- Human tele-operator remains in overall control.
- Sensors only change directions and speed when needed.
- The movement requested of the robot was achievable.

Imagined potential fields were placed round objects within the range of the sensors [5, 21]. The sensor system routinely adjusted the length of the pulses as ranges to objects changed. If no obstacles were sensed then the range-finder steadily lengthened the pulses in order to increase range until an object was found and that gave earlier warnings about potential problems.

B. *Mapping the environbment ahead of the mobile robot*

Ultrasonics can be noisy and can return false readings. These were filtered out using Histogramic In-Motion Mapping. The volumes ahead of the robot were divided into right and left lattices, with CLOSE, INTERMEDIATE and FARAWAY, cells within the grid. A central volume was also created where the sensors overlapped, if objects were detected by both sensors. When something was detected ahead of the robot then it was categorised as CLOSE, INTERMEDIATE or FARAWAY. The sensors were attached to the mobile robot chassis so that their rays over-lapped and enclosed the volume ahead of the robot.

The nine array elements represented a volume where objects could be detected. If anything was detected then the element(s) associated with that cell were increased with a relatively large value, e.g.: six, up to a limit of sixteen. Other cells in the grid decreased by smaller amounts, for example two, down to a final value of zero. This all gave a histogrammic depiction of the volume ahead of the robot with nine cells. If an obstacle entered any of the cells then that cell quickly increased in value. Unintended and random misreading in other cells only increased for the single misreading and then the value of the cell reduced. If the object materialised within another cell then the new cell quickly increased and when the object disappeared out of the original cell then it's value reduced to zero. A reliable range was attained in less than 0.5s.

C. *Interpreting the joystick*

The mobile robot base used a Penny & Giles joystick containing 2 x potentiometers. Joystick position was determined with two A/D converters.

The joystick data was in Cartesian coordinates but they were translated into polar coordinates: $J|\angle\theta$.

$|J|$ was a measure of how far a joystick was moved off-centre. That showed how fast an operator wanted the robot to go. Angle $\angle\theta$ was the preferred direction of travel.

The time that a joystick stayed in the same position suggested how confident the operator was in their decision.

$|J|$ was evaluated by means of:

$$|J| = \sqrt{((JSA*JSA)+(JSB*JSB))} \quad (1)$$

JSA and JSB were Cartesian co-ordinates.

$|J|$ and θ were used to establish the position of the joystick and therefor the desired direction and speed. Confidence and position were recorded in an array with each cell comprising 2 x values:

- "*Angle Confidence*" indicated whether the position of a joystick was remaining steady.
- "*Magnitude*" specified required mobile robot speed.

Joystick input was an input to the rule based system and it provided a confidence-level of user intentions.

The histogrammic depiction also represented a pseudo-integrator. If an operator held a joystick in one position, then the cell associated with that place increased in value. The other elements decremented. The element with the biggest value represented joystick position.

A computer procedure *JoystickArray* calculated which cell a joystick occupied and the associated "angle confidence" (*AngleConf*) increased. Other un-occupied cells decreased. So, histogram elements quickly reduced in value but built up in value slower.

JoystickArray cells increased to maximum in approximately 0.5s and reduced to zero in approximately 150 ms.

Weights to dictate the amount of increase or decrease were found experimentally. Specific weights could be set for individual human operators or for explicit tasks.

III. KINEMATICS OF A BOBCAT II BASE

The kinematics of the tele-operated mobile robot (Fig. 1) are described here. The robot had two large driving wheels at the front.

Movement and direction were accomplished by turning the driving wheels separately. Wheel radius was designated as r and diameter was then 2r. (Fig 2).

Using notation from [1], the driving wheels were W distance apart. C was the centre of gravity of the mobile robot. P was at the intersection of a line through the centre of the robot and another through the wheel axis. d was distance between C and P.

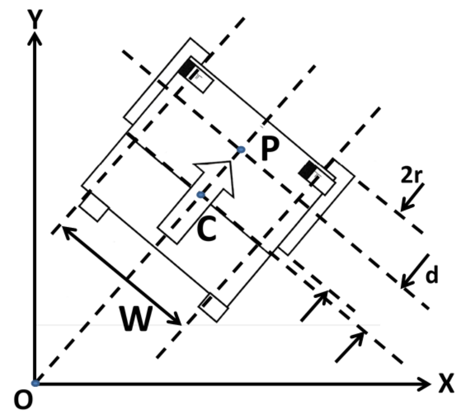

Fig 2 Geometry of the tele-operated mobile robot

Kinematics for the tele-operated mobile robot is in Fig. 3. It was assumed that no slip existed between the wheels and the floor.

$$v_{tang} = 1/2\ (v_{right} + v_{left}) \quad (2)$$

$$\omega_{tang} = 1/W\ (v_{right} - v_{left}) \quad (3)$$

$$v_{right} = r\omega_{right} \quad \text{and} \quad v_{left} = r\omega_{left} \quad (4)$$

where ω is angular velocity and v is linear velocity of the tele-operated mobile robot.

The position of the mobile robot in global coordinates is [O X Y] and in vector notation is:

$$\boldsymbol{q} = [\ x_C\ y_P\ \theta]^T \quad (5)$$

where x_C and y_P are global coordinates of P (Fig. 2). θ is the orientation of $[\ P\ x_C\ y_P\ ]$, the local coordinate frame on the tele-operated mobile robot in Fig. 3. determined from the horizontal axis. The coordinates define the configuration of the mobile robot (5). The tele-operated mobile robot is rigid and wheels are assumed not to slip so that the tele-operated mobile robot can only move normal to the wheel axis.

So, velocity at the point of contact with the ground (and orthogonal to the plane of the wheel) is zero.

$$(dy_P/dt) \cos\theta - (dx_C/dt) \sin\theta - d\theta/dt = 0 \quad (6)$$

Kinematics restrictions do not depend on time, and so are

$$A^T(\boldsymbol{q})\, d\boldsymbol{q}/dt = 0 \tag{7}$$

where $A(\boldsymbol{q})$ is an input matrix associated with constraints and $C^T A(\boldsymbol{q}) = 0$ (8)

where $C(\boldsymbol{q})$ is a full-rank matrix formed by a set of linearly independent vector fields covering the null space of $A^T(\boldsymbol{q})$. v_{tang} is a vector time function that can be found for times t from equations (7) and (8).

$$d\boldsymbol{q}/dt = C(\boldsymbol{q})\, \boldsymbol{v}_{tang} \tag{9}$$

For a tele-operated mobile robot the constraint matrix in (6) is

$$\mathbf{A}^T(\boldsymbol{q}) = [-\sin\theta \ \cos\theta \ -d] \tag{10}$$

And

$$\boldsymbol{v}_{tang} = [v \ \omega\ ]^T \tag{11}$$

Where ω is angular velocity and v is linear velocity of point P (along the tele-operated mobile robot axis).

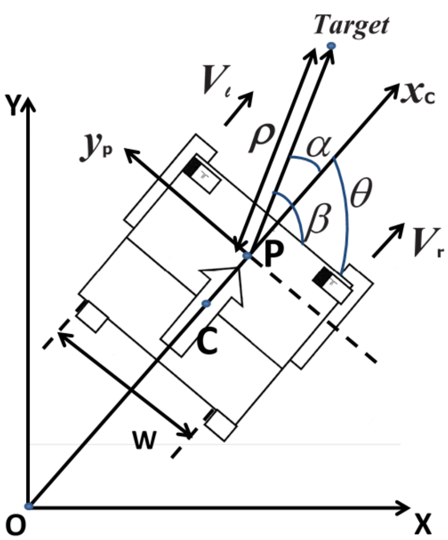

Fig 3 The kinematics of the tele-operated mobile robot

Therefore, the kinematics (9) can be described in a dq/dt matrix.

As the tele-operated mobile robot only tends to move forwards then $v = -v_{,ang}$ and the system can be portrayed by a new simplified matrix. A controller was required to generate wheel velocities and steering angle was

Steering Angle = $(v_{left} - v_{right})/W$,

to drive the tele-operated mobile robot to follow the designated route.

IV. CONTROL AND THE RULES

v and ω were calculated to move the powered wheelchair from its current configuration, for example $\rho_0\, \alpha_0\, \beta_0$, to the target position.

Considering linear control [30]

$$v = K_\rho \rho \tag{12}$$

$$\omega = K_\alpha \alpha + K_\beta \beta \tag{13}$$

This closed-loop system could be depicted by a matrix to drive the mobile robot to $(\rho, \alpha, \beta) = (0,0,0)$, the target destination.

The controller was tested in simulation and then mounted onto the mobile robot. It had an overdamped response.

Joystick input and input from the ultrasonics were combined using a set of rules designed to avoid obstacles. These were later improved to include a more global target destination (a via point) to help the tele-operators follow a more efficient global route.

The initial rules combined four inputs to avoid objects in the path of the mobile robot (fig 4). They were:

- Joystick steering angle;
- Distance to objects detected by both sensors;
- Distance to objects to the left of the robot;
- Distance to objects to the left of the robot.
-

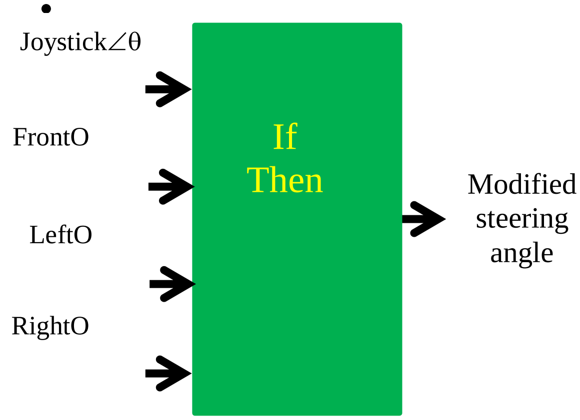

Fig. 4. Initial rule-based system.

Sensor input concerning the surroundings of the robot were used to modify the steering angle used in the controller. The suggested path would be safe and efficient for tele-operated mobile robot movement. If ∠θ was to the right of the tele-operated mobile robot then it tended to turn clockwise but if ∠θ was to the left then the tele-operated mobile robot turned anticlockwise.

The control systems worked well but in an effort to improve function if human sensors were impaired (for example, if an operator could not see the mobile robot for any reason). Rules were modified to incorporate a new via point as a target destination to aid the tele-operators if they needed more help (fig. 5.).

The rule based system now had a target via point to consider in addition to knowledge of the environment in front of the robot and a joystick steering angle. That increased the number of rules considerably.

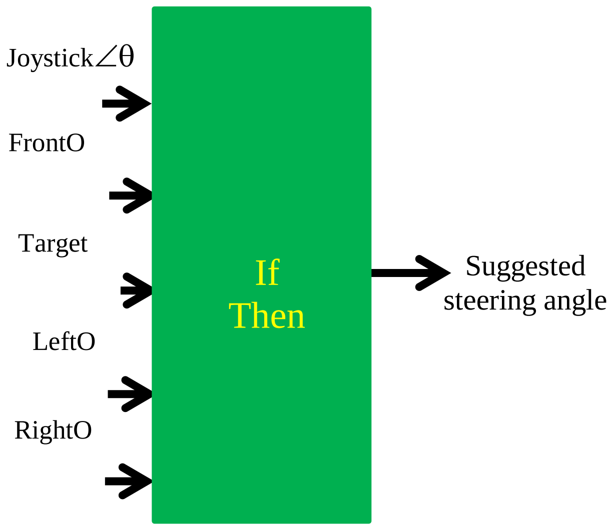

Fig. 5. The revised –rule-based system.

The rules in their revised from are described here:

CASE 1 - the obstacle and destination are on left of the tele-operated mobile robot:

Rule1: *If* Joystick=0^{O} *and* LeftO=INTERMEDIATE *and* RightO ≤ FARAWAY *and* FrontO ≤ FARAWAY *and* TargetAngle=75^{O}, *then* suggested change in steering angle=0^{O}

Rule2: *If* Joystick=0^{O} *and* LeftO=INTERMEDIATE *and* RightO ≤ FARAWAY *and* FrontO ≤ FARAWAY *and* TargetAngle =60^{O}, *then* suggested change in steering angle=-10^{O}

Rule3: *If* Joystick=0^{O} *and* LeftO=INTERMEDIATE *and* RightO ≤ FARAWAY *and* FrontO ≤ FARAWAY *and* TargetAngle =50^{O}, *then* suggested change in steering angle=-25^{O}

CASE 2 - the obstacle and destination are on the right of the tele-operated mobile robot:

Rule4: *If* Joystick=0^{O} *and* LeftO ≤ FARAWAY *and* RightO = INTERMEDIATE *and* FrontO ≤ FARAWAY *and* TargetAngle=75^{O}, *then* suggested change in steering angle=15^{O}

Rule5: If Joystick=0^{O} *and* LeftO= ≤ FARAWAY and RightO = INTERMEDIATE *and* FrontO ≤ FARAWAY *and* TargetAngle =60^{O}, *then* suggested change in steering angle=30^{O}

Rule6: *If* Joystick=0^{O} *and* LeftO= ≤ FARAWAY *and* RightO = INTERMEDIATE *and* FrontO ≤ FARAWAY *and* TargetAngle =30^{O}, *then* suggested change in steering angle=25^{O}

CASE 3 - an obstacle is in front and the destination is on the right:

Rule5: *If* Joystick=0^{O} *and* LeftO= CLOSE *and* RightO = CLOSE *and* FrontO ≤ FARAWAY *and* TargetAngle =20^{O}, *then* suggested change in steering angle=15^{O}

Rule6: *If* Joystick=0^{O} *and* LeftO= CLOSE *and* RightO = CLOSE *and* FrontO ≤ FARAWAY *and* TargetAngle =25^{O}, *then* suggested change in steering angle=20 ^{O}

Rule7: *If* Joystick=0^{O} *and* LeftO= CLOSE *and* RightO = CLOSE *and* FrontO ≤ FARAWAY *and* TargetAngle =30^{O}, *then* suggested change in steering angle=25^{O}

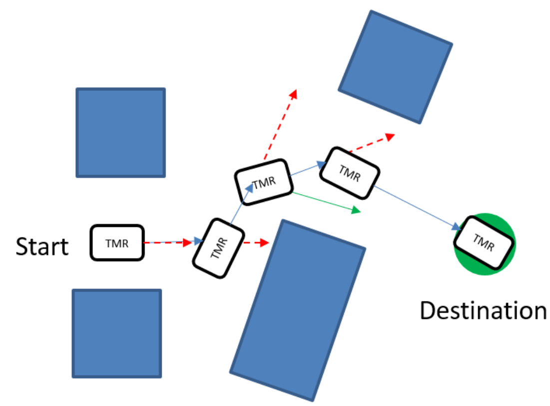

Fig. 6 Robot moving through obstacles using the revised rule set showing approach directions (solid line) and calculated directions (dashed line).

The system worked better with the new rules and especially assisted drivers when human sensors were not working fully. The path of the robot is shown again in Fig. 6. with the additional rules. The extra arrow is the angle to the destination.

V. TESTING AND RESULTS

Systems were simulated and a typical simulation is shown in Fig. 7.

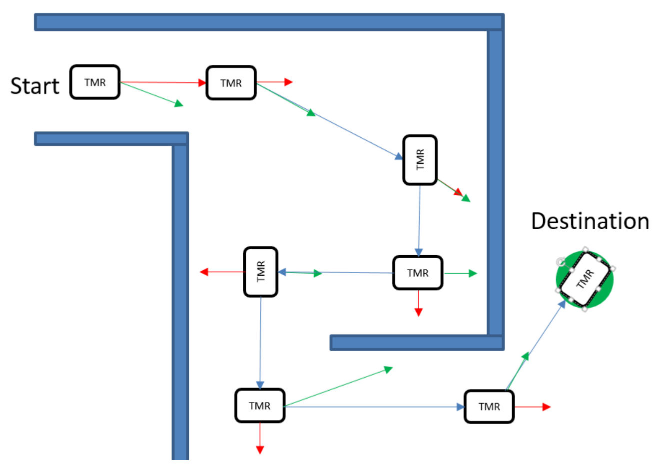

Fig. 7 A typical simulation using the revised set of rules showing the mobile robot avoiding local minima (for example the inner wall corners).

After simulations had successfully tested the algorithms, the software and hardware was mounted on the mobile robot base. For each test with the robot, a standard course at the University of Portsmouth was set.

The tele-operated mobile robot avoided obstacles. When ultrasonic sensors detected an object close to the mobile robot, the robot avoided collision by turning away. That avoidance could be overruled by the joystick if the tele-operator wanted the robot to move close to the object.

Avoidance activated when sensors were FARAWAY or closer. If sensors detected an object ahead while moving in the direction of the destination, then the mobile robot turned to move alongside the object. When there were no objects in the way, and the joystick was held in a forward position, the robot steered towards the target destination. That tended to reduce the time taken to get to destinations by a significant amount when vision was impaired (perhaps due to smoke etc). The rule-based system adjusted direction and quickly moved towards the target destination.

Results from simulation and from a real time experiment with the tele-operated mobile robot are shown in Fig. 6. and Fig. 8. As examples of how the systems were validated.

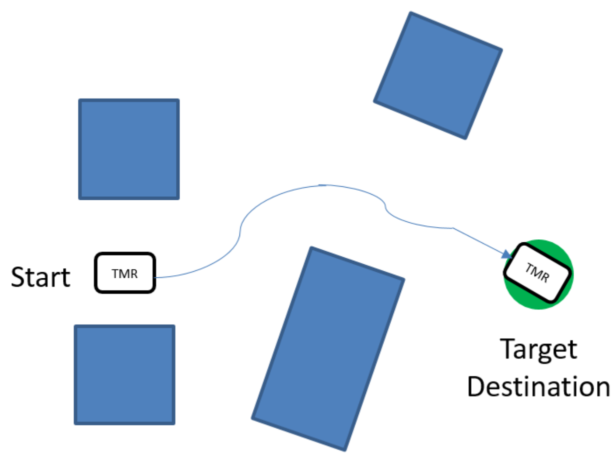

Fig. 8 Results from a real time experiment with the same rules applied.

Results were compared with those obtained using the systems in [1]. The rule-based system tended to perform better than the previous systems in terms of time taken to complete a path. Figure 9 shows a comparison of time taken by the systems as the tele-operated mobile robot was driven through a set of standard test environments at the University of Portsmouth.

Average time to complete a course was less for the new systems in most cases. There are two anomalies in figure 10. As environments became more complex they needed more turnings, for example to reach a target destination, the mobile robot may need to move through more than one room. Including the destination as an extra input made tele-operation a little less efficient in easy sections of a route and when the tele-operator could see what was happening. In those cases, the operator did not need a sensor system to help them. As an example, two routes are shown in Fig. 11 and Fig. 12.

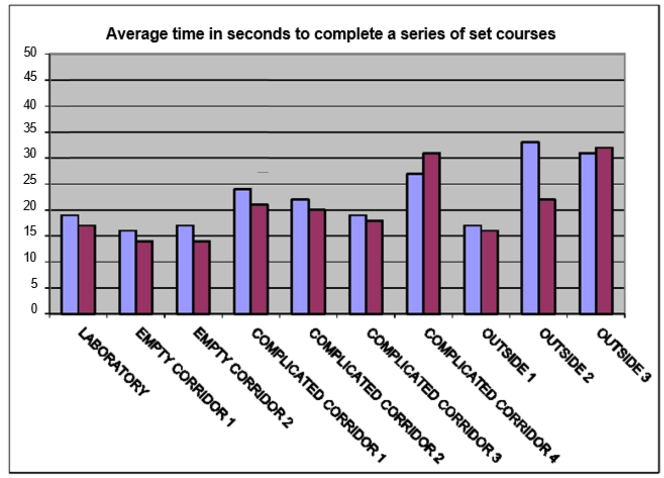

Fig. 9 Comparison between systems; showing average time taken to complete a series of set courses from a start point to a destination. Left hand bars show time taken without sensors to assist and right hand bars show time taken with sensors to assist.

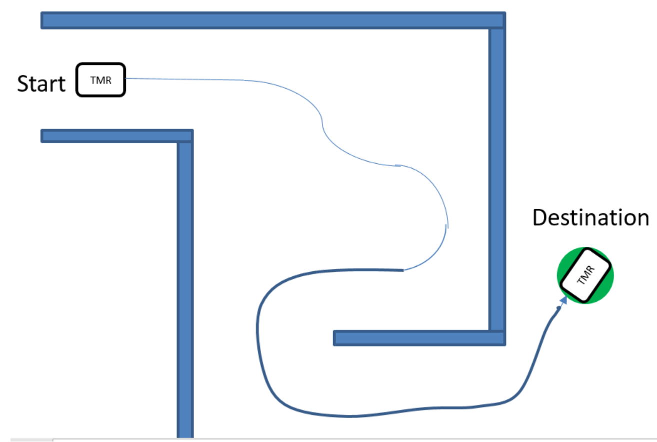

Fig 10 shows the path of a robot using the revised rules when the tele-operator cannot see the robot,.

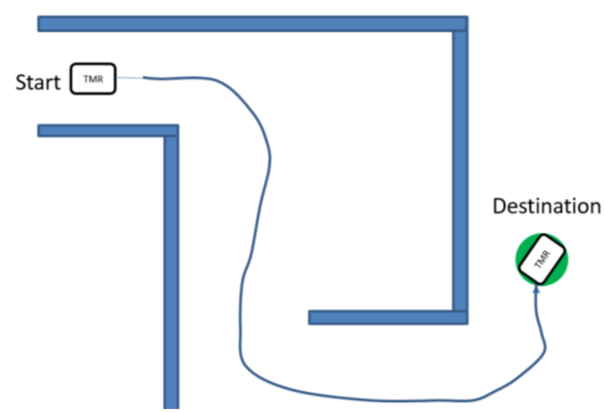

Fig 11 shows the path of a robot using the revised rules when the tele-operator can see the robot,..

In Fig. 10, the rules tended to pull the robot towards the destination. The original rules just depended on angular input from the joystick, $\angle\theta$. The path is less efficient but is completed despite not being able to see the robot. The difference is shown in Fig. 12.

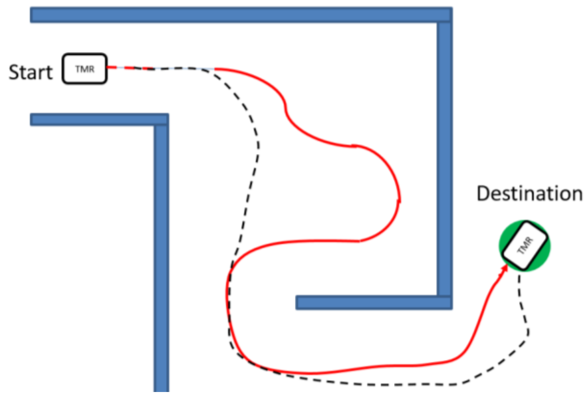

Fig 12 shows the difference in the paths of a robot using the revised rules when the tele-operator can see the robot (dotted) and when the robot relies only on the sensors (solid line).

If a driver is capable of steering a robot quite well and they can see the robot then they can overcome the rules that might make the route less efficient.

The tele-operated mobile robots were able to reach destinations efficiently.

The methods provided a faster response in most cases and reduced the amount of computation time compared with other approaches and the rule-based system performed as effectively.

A real time path is shown in Fig. 11.

The tele-operated mobile robot needed to avoid static and moving obstacles and objects (for example human beings walking close to the robot).

When sensors received information about objects close to the tele-operated mobile robot, then the mobile robot avoided collision by turning away.

Collision avoidance was a high priority for the tele-operated mobile robot and initially overrode other behaviours, however if the joystick remained fixed (roughly) in a particular position then that input was integrated over time and the wishes if the tele-operator overrode that behaviour.

When the inputs from the sensors rose above a threshold within an array cell then avoidance was activated.

When the tele-operated mobile robot detected an obstacle in front while moving toward a target destination (via point) then wall-following behaviour was applied; the mobile robot tended to rotate to align with and then move parallel to the wall.

When sensors were not detecting anything, then the system drove in a direction that was an average between the angle to the target destination and the angle requested by the joystick. If the joystick was roughly in alignment with the direction of the target destination, then rules adjusted the direction of the mobile robot and sent it towards the target destination.

Results were compared with those obtained from recent alternative systems and the rule-based system performed well.

VI. CONCLUSIONS

The rule-based system is safe and robust. It is uncomplicated and efficient in assisting a tele-operator with steering / driving a mobile robot.

Rule based methods were applied successfully. The mobile robot rapidly acknowledged objects around it and assisted operators in completing their tasks.

Simulated paths were compared with tests in the laboratory and that validated the rules, the use of the rules and the robot systems.

The system compared favourably with recent systems in the literature and that also validated the techniques.

Work is now investigating mixing other AI tools [31-40] in order to use specific tools where they can have most effect.

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