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Simulator for Control of Autonomous Nonholonomic Wheeled Mobile Robot

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Abstract: The study presents a Virtual Reality (VR) technique that is used in the construction of a nonholonomic Wheeled Mobile Robot (WMR) simulator for the experimentation of robotic control algorithms. The modelling of the proposed simulator involves motion planning, motion control and the application of a VR technique that employ a number of strategies and algorithms. The role of a trajectory planner as the interface mechanism between the motion planner and controller is particularly highlighted to facilitate the overall design of the simulator. The interlinking between the main components is also relevantly described prior to the execution of a simulation study that takes into account a number of operating and loading conditions. A case study includes the application of different control schemes to the WMR that is executing a tracking task with disturbances applied at its actuators in a virtual Computer Integrated Manufacturing (CIM) environment. Results of the study indicate the effectiveness of the proposed simulator in demonstrating the WMR capability to manoeuvre desirably towards its target destination while at the same time avoiding the collision with obstacles along its traveled path.

Key words: Active force control, motion control, motion planning, virtual reality, simulator

INTRODUCTION

In the past two decades, significant progress in robotic research have brought about rapid advancement in both theory and application of nonholonomic WMR in areas ranging from flexible manufacturing, daily household services to space exploration. This is due to the drastic improvements in recent computing technology which has greatly facilitated the study of robotics. In order to study an algorithm for generating a behaviour of the robot, it is important to make quantitative evaluation of the algorithm through repetitive trials and experimentations. This is in fact not an easy task in real-world operation whilst required excessive operation cost (Safaric *et al*., 2003; Magnusson, 2005). To counter this, a WMR simulator is required to perform repetitive virtual experiments on the newly modelled algorithms. Generally, in robotics experiment, it is not necessary to have a physical robot and thus the hardware of the robot is actually incidental in this case. It is the software that differentiates a robot from a machine.

WMR simulator is in fact not a new issue in robotics study. It generally involves various subfields or disciplines, namely motion planning, motion control and the application of VR. From the past, both motion planning and motion control algorithms have been extensively studied by researchers worldwide. However, very few researchers have focused on the integration of these two subjects into the construction of a WMR simulator. Most of them either aim at the construction of the motion planner (Cameron, 1994; Lamiraux and Laumond, 2001; Van den Berg and Overmars, 2005) or concentrate on the modelling of the motion controller (Fierro and Lewis, 1998; Dixon *et al*., 2000; Pourboghrat and Karlsson, 2002; Oriolo *et al*., 2002; Coelho and Nunes, 2005). Since the development of the proposed virtual WMR simulator requires a direct link between the motion planner and the motion controller, it is proposed that a trajectory planner should be modelled in such a way that it is capable of transforming the geometrical outputs of the motion planner into the time-indexed trajectory which is then fed into the motion controller as the reference trajectory.

In Spence and Hutchinson (1995), a different method of integrating motion planner and motion controller has been reviewed where the motion planning algorithm is directly incorporated into the motion control scheme through an inverse dynamic controller and a robust control structure. Meanwhile, Yung and Ye (1997) have developed a fully integrated mobile vehicle simulator (known as EXPECTATIONS) which is capable in path planning, behaviour learning, collision avoidance and navigation in the specified Virtual Environment (VE). However, the proposed WMR simulator has neglected the

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dynamic effects of the nonholonomic WMR. On the other hand, Howard *et al*. (2005) have introduced a hierachical strategy which consists of both global and regional path planner to generate a series of reactive control actions in terms of desired manoeuvering speed and turns through the utilization of fuzzy logic construct. The dynamic effect of the nonholonomic constraints is inherently embedded into the fuzzy rules that have been developed. In other words, a fine setting of fuzzy rules and complete understanding of the system behaviours are essential in promising a soundful and effective run of the robot.

In this study, a trajectory planner that acts as the interface of motion planner and motion controller in the construction of the virtual WMR simulator has been modelled through parametric cubic spline interpolation method. It is in fact an extension to the previous work done in Mailah *et al.* (2006) but with different operating and loading conditions. It is thought that the inclusion of the trajectory planner in motion planner and controller (that has not been rigorously addressed by most of the previous researchers) greatly facilitates the design and construction of the WMR simulator.

OVERALL ARCHITECTURE OF WMR SIMULATOR

The WMR is assumed to be located on a two dimensional plane in which a global Cartesian coordinate system is defined at the reference point, O. The heading direction, $\phi(t)$ is taken positive in counter-clockwise from x-axis as shown in Fig. 1 which depicts the configuration of a differentially driven WMR. For the navigation of the WMR, two coordinate axes are applied: global x-y axis and local v-n axis.

The construction of the WMR simulator involves the study of motion planning, motion control and the application of VR technique. Thus, in order to ensure a systematic and effective simulation study, the coordination and inter-relationship between all these subfields have to be carefully planned and implemented. The integration of all these subfields is shown in Fig. 2.

The map of the workspace for the virtual mobile robot is first captured by a virtual camera which is installed within the VE. The map which is represented in bitmap form is then interpreted and analyzed for the generation of the configuration space, C and search space using algorithm such as the six elementary jumps graph (Podsedkowski *et al*., 2001). From this generated six elementary jumps graph, the path planner searches for a near-optimal time-independent collision-free path through an A* heuristic search algorithm. Since the motion controller requires the input in the form of a time-based

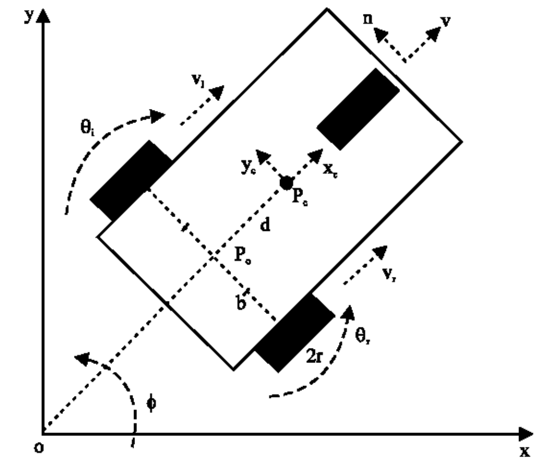

Fig. 1: Configuration of a WMR

The notations used in the Fig. 1 are described as follows:

b	:	Distance between driving wheels and axis of geometry
d	:	Distance between P_0 and P_c
P_c	:	mobile robot's reference point
P_0	:	Middle point of the axis of rotation for wheels
r	:	Radius of wheel
v	:	Linear velocity
x	:	Current position of mobile robot in *x*-axis
y	:	Current position of mobile robot in *y*-axis
ϕ	:	Current orientation of mobile robot
θ	:	Wheel rotation
Subscript c	:	Location at the centre of gravity of the WMR
Subscript r	:	Right
Subscript l	:	Left

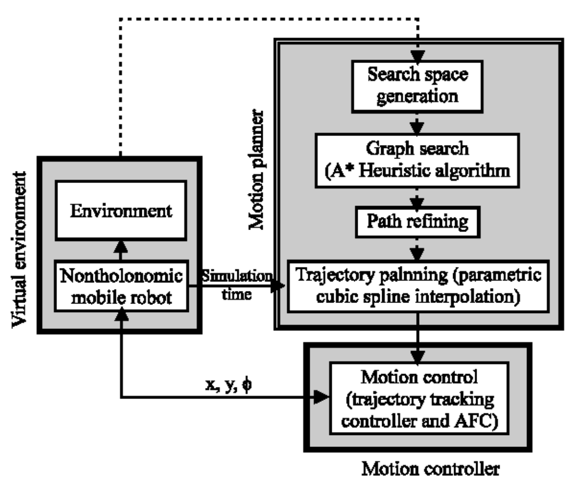

Fig. 2: Interlinking of motion planning, motion control and a VR technique

reference trajectory, this geometrically planned collision-free path has to be transformed into a function of time. For this purpose, the concept of parametric cubic spline interpolation has been applied for the modelling of the trajectory planner. With this generated time-indexed reference trajectory, the motion controller comprising the Resolved Acceleration Control (RAC) and Active Force Control (AFC) will generate the necessary control acceleration command signals and actuating torque respectively to drive and navigate the WMR towards its destination through appropriate path within the VE. The current states of the WMR are continuously fed-back for the trajectory tracking control purpose. The design and incorporation of the three main elements of the proposed WMR simulator shall be individually discussed in the following sections.

MOTION PLANNING

The proposed motion planning concentrates mainly on global collision-free path planning in a known stationary environment (CIM facility). This necessitates the construction of a sequence of movements in C which connects the initial and target WMR's configurations such that the robot has no contact or collision with obstacle spaces (Hwang and Ahuja, 1992). The procedures involved in global collision-free path planning are as shown in Fig. 3, where it begins with the definition of the initial and goal states of the mobile robot. It should be noted that a number of different path planning algorithms are shown in the respective blocks though only the elementary jumps graph technique (for the search space generation) and A* algorithm (for the graph searching method) were actually being implemented in the study. The next step is the topographical mapping that is typically represented in a bitmap form. From this map, a search space for the mobile robot is generated. During the construction of the search space, the effective working region of the mobile robot is classified into forbidden and free regions where the mobile robot is logically prohibited from entering the forbidden region while it is permitted to work in the free region. Figure 4 shows the six-elementary jumps graph which has been used for the selection of potential collision-free nodes.

For planar application, a WMR usually has three Degree of Freedom (DOF) and the C dimension of the robot is $\Re^2 \times S^1$, representing the position and orientation of the WMR where S' is in unit cycle (Laumond *et al.*, 1994). With the application of six-elementary jumps graph, the dimension of path searching space can actually be reduced to $\Re^2$ in which S' can be eliminated through appropriate selection of the successors during the graph

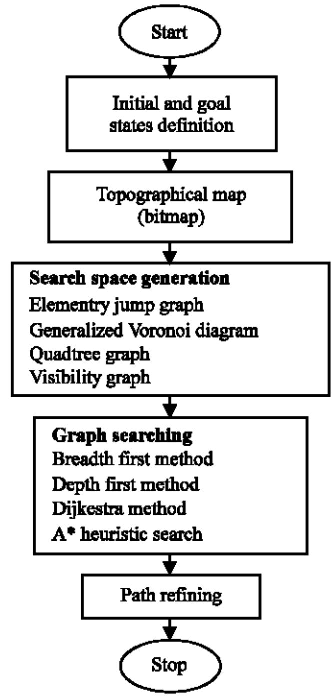

Fig. 3: Flow chart of global collision-free path planning

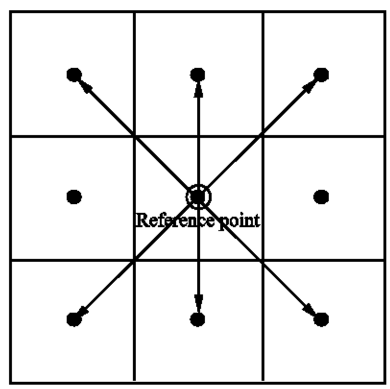

Fig. 4: Six-elementary jumps in the selection of potential successors

searching. The arcs of motion which fulfil the nonholonomic constraint are generated through six elementary jumps: forward right, forward left, forward straight, backward right, backward left and backward straight (Podsedkowski *et al.*, 2001). From all these feasible arcs of motion which are free from obstacles, several possible sequence of actions which will lead the mobile robot to the destination point are searched during the graph searching stage through an A* heuristic search technique. The heuristic algorithm is a method for computing the shortest path from one given start node to one given goal node by using special knowledge about the domain of the graph problem (Trovato and Dorst, 2002). The potential path which has the minimum cost is then selected. Finally, the output of the graph searching has to be refined in order to remove the unwanted cusps from the planned collision-free path.

TRAJECTORY PLANNER

The motion planner generates only a geometrical collision-free path and it is not ready for use by the motion controller which specifically requires the time-based trajectory as the input. Therefore, the geometrical collision-free path has to be redefined into a time-based trajectory before it is fed into the motion controller for the trajectory tracking control (Jamhour and André, 1996). For this purpose, a trajectory planner has to be modelled in such a way that it is able to approximate the desired shape of the path curves and transforming them into time based functions. The generated trajectory functions should in effect also use less memory storage and able to offer easier manipulation of the collision-free path. It is assumed that the geometrical collision-free path is actually a sequence of points in three dimensional space (x, y, ϕ) through which the mobile robot is required to follow. In this study, a parametric cubic spline function is applied for the description of the trajectory function. This is due to the fact that the parametric cubic representation of curves, i.e., $x = x(t)$, $y = y(t)$ and $\phi = \phi(t)$ is able to overcome the problems caused by the functional or implicit forms. Parametric cubic spline interpolation also surpasses B-spline interpolation since B-spline interpolation fails to pass through all of the trajectory knots whilst parametric cubic spline interpolation does (Cao *et al*., 1997). The general form of the parametric cubic spline function is given as:

$$q(t) = a_1t^3+a_2t^2+a_3t+a_4 \quad (1)$$

Where:

a_1 : 3rd order coefficient for cubic spline function
a_2 : 2nd order coefficient for cubic spline function
a_3 : 1st order coefficient for cubic spline function
a_4 : 0th order coefficient for cubic spline function

With reference to Eq. 1, the parametric cubic polynomials that define a segment of the path with reference to t, $q(t) = [x(t)\ y(t)\ \phi(t)]$ are as follows:

$$\begin{aligned} x(t) &= a_{1x}t^3 + a_{2x}t^2 + a_{3x}t + a_{4x} \\ y(t) &= a_{1y}t^3 + a_{2y}t^2 + a_{3y}t + a_{4y} \\ \phi(t) &= a_{1\phi}t^3 + a_{2\phi}t^2 + a_{3\phi} + a_{4\phi}, \qquad 0 \le t \le 1 \end{aligned} \quad (2)$$

With the assumption that the initial and goal states of the mobile robot are zero, a boundary condition can be generated for the geometrical path which consists of n points as follows (Jamhour and André, 1996):

$$q_1' = q_1'' = q_n' = q_n'' = 0 \quad (3)$$

Continuity constraints are also assumed to exist between the spline segments by enforcing continuity of acceleration between neighbouring segments. Through this assumption together with the boundary condition as shown in Eq. 3, the coefficients a_1, a_2, a_3 and a_4 can be calculated as shown in (Cook and Ho, 1985). The velocity (q) and acceleration (q) of the WMR can be obtained through the first and second derivatives of Eq. 1 as follows:

$$\begin{aligned} q'(t) &= 3a_1t^2 + 2a_2t + a_3 \\ q''(t) &= 6a_1t + 2a_2 \end{aligned} \quad (4)$$

MOTION CONTROLLER

Since the WMR does not meet Brockett's well-known necessary smooth feedback stabilization condition (Brockett, 1983), it can not be stabilized to a point with smooth static-state feedback control laws. Thus, instead of stabilizing the WMR to a point, the proposed mobile robot system is required to converge only to a reference trajectory which is in line with suggestion by Walsh ***et al.*** (1994). Noting **M, V, A, D, E,** q, τ and λ as symmetric and positive definite inertia matrix, centripetal and Coriolis matrix, disturbance matrix, matrix related to nonholonomic constraint, input transformation matrix, states of motion as a function of (x, y, ϕ), control torque input vector and Lagrange multiplier respectively, the dynamic model of the WMR is given by (Yamamoto and Yun, 1994), (Coelho and Nunes, 2005):

$$\mathbf{M}(q)\ddot{q} + \mathbf{V}(q,\dot{q}) + \mathbf{D} = \mathbf{E}(q)\tau - \mathbf{A}^T(q)\lambda \quad (5)$$

Referring to Fig. 5, the motion controller for the nonholonomic WMR essentially consists of two types of controllers, namely the Resolved Acceleration Control (RAC) serving as a kinematic-based controller manipulating the outermost loop and Active Force Control (AFC) acting as a disturbance compensator embedded in the inner loop.

RAC is responsible for the generation of the acceleration command signals with reference to the desired trajectories. The equations for the generation of the acceleration command signals (variables with subscripts com) are expressed as follows (Luh *et al*., 1980):

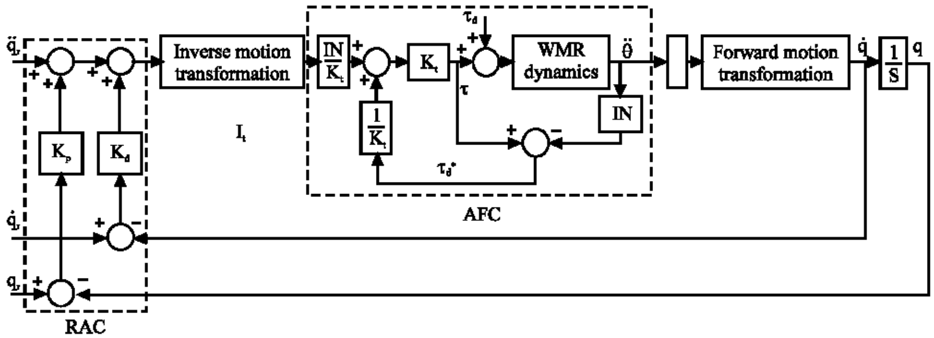

Fig. 5: Block diagram of the proposed motion controller (Mailah *et al.*, 2006)

$$\begin{aligned}\ddot{x}_{com} &= \ddot{x}_{ref} + K_{dx}(\dot{x}_{ref} - \dot{x}) + K_{px}(x_{ref} - x)\\ \ddot{y}_{com} &= \ddot{y}_{ref} + K_{dy}(\dot{y}_{ref} - \dot{y}) + K_{py}(y_{ref} - y)\\ \ddot{\phi}_{com} &= \ddot{\phi}_{ref} + K_{df}(\dot{\phi}_{ref} - \dot{\phi}) + K_{pf}\sin(\phi_{ref} - \phi)\end{aligned} \quad (6)$$

Where:

$\ddot{x}$	:	Linear acceleration in x direction
$\ddot{y}$	:	Linear acceleration in y direction
$\ddot{\phi}$	:	Angular acceleration with respect to the heading angle
$\dot{x}$	:	Linear velocity in x direction
$\dot{y}$	:	Linear velocity in y direction
$\dot{\phi}$	:	Angular velocity with respect to the heading angle
K_d	:	Derivative constant
K_p	:	Proportional constant
Subscript ref	:	Reference signal

The generated acceleration command signals are then transformed from global axis to local axis according to the following transformation:

$$\begin{bmatrix}\ddot{x}_{local}\\ \ddot{y}_{local}\\ \ddot{\phi}_{local}\end{bmatrix} = \begin{bmatrix}\cos\phi & \sin\phi & 0\\ -\sin\phi & \cos\phi & 0\\ 0 & 0 & 1\end{bmatrix}\begin{bmatrix}\ddot{x}_{global}\\ \ddot{y}_{global}\\ \ddot{\phi}_{global}\end{bmatrix} \quad (7)$$

Since the total DOF for the WMR is three whereas the controllable DOF is two, the DOF for the solution of Eq. 7 has to be stepped down to two. Following works by Kanayama *et al.* (1990), a converter with ξ set to unity has been proposed as follows:

$$\begin{bmatrix}\dot{v}\\ \dot{\omega}\end{bmatrix} = \begin{bmatrix}\ddot{x}_L\\ \xi\,\ddot{y}_L + \ddot{\phi}_L\end{bmatrix} \quad (8)$$

For the AFC part, noting IN and τ as the estimated inertia matrix, measured acceleration signal and applied control torque respectively, the estimated disturbances τ_d^* can be obtained as follows (Hewit and Marouf, 1996) (Kobayashi *et al.*, 2007):

$$\tau_d^* = \tau - \mathbf{IN}\ddot{\theta}_{act} \quad (9)$$

Generally, the main requirement of the AFC scheme is the estimation of IN. In this research, IN is chosen from the finite bound of the modelled inertia matrix, M such that (Mailah, 1998):

$$IN = K \quad (10)$$

where, $0.4\,M < K < 1.2\,M$.

CONSTRUCTION OF THE SCENE GRAPH FOR VIRTUAL ENVIRONMENT

The virtual simulator is constructed based on the actual CIM facility at the Industrial Automation Laboratory, Faculty of Mechanical Engineering (FME), Universiti Teknologi Malaysia (UTM). The VE for the CIM facility is actually modelled through WorldToolKit® (WTK) software and it generally contains a number of objects, such as the lights, positional information, fogs and geometries. In order to manage all these objects systematically, WTK uses the concept of scene graph, where the whole structure of VE is maintained in a hierarchical structure (Engineering Animation, 1999). Figure 6 shows the hierarchical structure of a VE relating to a portion of the scene graph that has been constructed in the study pertaining to the CIM facility at the Industrial Automation Laboratory, FME, UTM.

VE structure typically resembles an upside-down tree formation since the root is at the top while the branches and leaves are at the bottom. All the objects in the VE are represented as nodes, which are the most fundamental elements of the scene graph. Each node contains the information about the physical objects and can be categorized into content node and grouping node. Content node, such as the geometry node, light node and transform node holds the information about the VE. Unlike the content node, grouping node does not hold

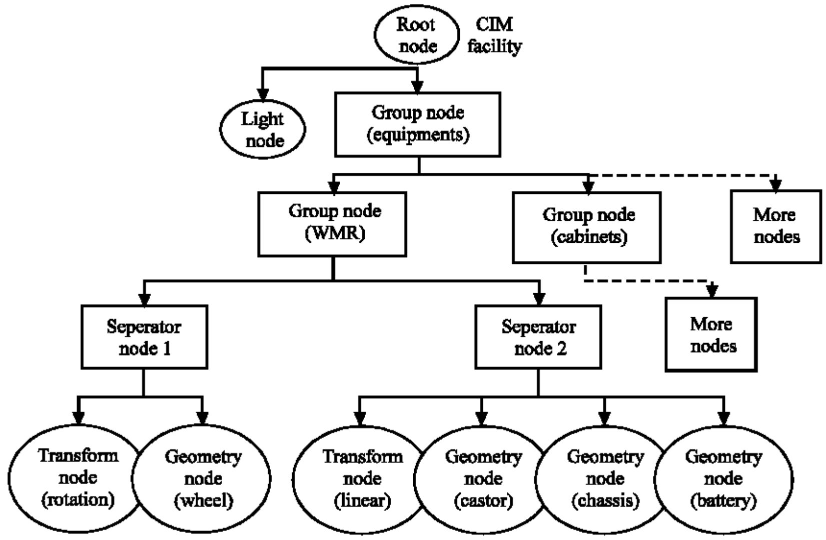

Fig. 6: Hierarchical structure of the scene graph for a VE pertaining to the CIM facility

any direct information about the VE. However, the presence of grouping node, such as the group node and separator node is essential in maintaining the hierarchical structure of the scene graph.

SIMULATOR SETUP

The WMR simulator is also developed using Microsoft Visual C^{++} and utilising the program-ready mathematical functions provided by the MATLAB library. This is in addition to the utilisation of the WTK package that is used in the construction of the VE for the CIM facility as mentioned in the previous section. The application of WTK has greatly reduced the programming burden for the VE rendering. For ease of program handling, the concept of object-oriented programming has been adopted. During the simulation, the WMR was required to plan for a collision-free path which was then transformed into a time-based reference trajectory. The obtained reference trajectory was then fed into the motion controller for the mobile robot trajectory tracking control. Meanwhile, the WMR was also perturbed from its reference trajectory by the constant and harmonic disturbance torques applied at the wheels to test system's stability and robustness. The simulation results were finally used for the motion transformation of the virtual mobile robot in the VE. A number of assumptions have been made during the construction of the virtual WMR simulator and are listed as follows:

Nonholonomic motion planning

Mobile robot perception sensors:	Assumed perfect models
Search space applied:	Six-elementary jumps graph
Graph searching method:	A* heuristic search
Trajectory planning method:	Parametric cubic spline interpolation

WMR parameters

Geometry of WMR:	r = 0.15 m, b = 0.75 m, d = 0.03 m
Mass of WMR:	m = 31.0 kg
Total mass moment of inertia of WMR:	$I = 15.625$ kg m^2
Moment of inertia for the wheels and the motor rotor about the wheel axis:	$I_w = 0.005$ kg m^2

RAC parameters

$K_{px} = 100$, $K_{py} = 100$ $K_{p\phi} = 100$, $K_{dx} = 10$, $K_{dy} = 10$, $K_{d\phi} = 10$

Active force control parameters

Motor torque constant: $K_t = \begin{bmatrix} 0.263 \\ 0.263 \end{bmatrix}$ Nm/A

Percentage of AFC: $K_c = \begin{bmatrix} 1.0 \\ 1.0 \end{bmatrix}$

Estimated inertia matrix: $IN = \begin{bmatrix} 0.5 \\ 0.5 \end{bmatrix}$ kg m^2

Applied disturbances

Constant torques at actuators: $\tau_a = \begin{bmatrix} 5 \\ -2 \end{bmatrix}$ Nm

Harmonic torques at actuators: $\tau_h = \begin{bmatrix} 6\sin(t)+3 \\ 2\sin(0.5t+\pi)+3 \end{bmatrix}$ Nm

Prior to the execution of the simulation program, a simple heuristic method was applied for the estimation of the controller gains, K_{px}, K_{py}, $K_{p\phi}$, K_{dx}, K_{dy} and $K_{d\phi}$. The obtained values of these gains were deemed suitable for the purpose of the simulation study. The AFC constant, K_c was set to 1.0 for full AFC implementation. For the simulation study, two types of motion control algorithms (RAC only without AFC and the other, RAC with AFC) were tested to examine the stability and robustness of the WMR. The performance of both motion controllers were compared for benchmarking purpose.

SIMULATION RESULTS AND DISCUSSION

Through the developed WMR simulator, the nonholonomic WMR with the appropriate control schemes was tested for its capability in collision-free path planning as well as trajectory tracking task. Figure 7-14 shows the simulation results produced by the proposed WMR simulator subject to various loading and operating conditions.

In Fig. 7, it is obvious that the WMR managed to achieve the global collision-free path which was then used for the trajectory tracking task in the virtual CIM layout. By incorporating the AFC scheme into the motion controller, the robustness of the robotic system has been greatly improved compared to the RAC only counterpart (without AFC) as shown in Fig. 8-10. The RAC with AFC scheme is able to generate the compensation torques necessary to reject most of the disturbance torques (τ_d^*) assuming that the angular acceleration () and actuated torques (τ) were accurately measured and that the estimated inertia matrix (IN) had been appropriately acquired in the AFC loop as governed by Eq. 9. The track errors as well as the orientation errors generated by the WMR with AFC are generally small and this small margin of errors has successfully kept the virtual WMR away from the obstacles. It is also noteworthy to mention that the RAC controller (without AFC) is sensitive to the application of external disturbances. This can be substantiated from the greater ripples that are significantly observed in the trajectory tracking error

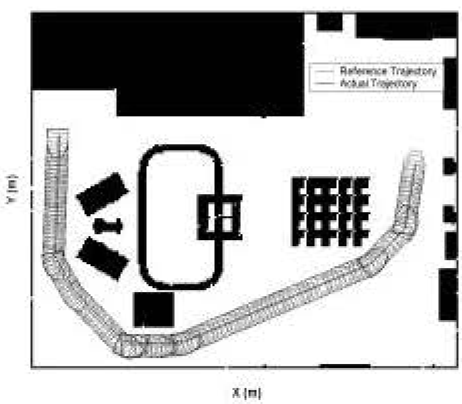

Fig. 7: Trajectory tracking in workspace

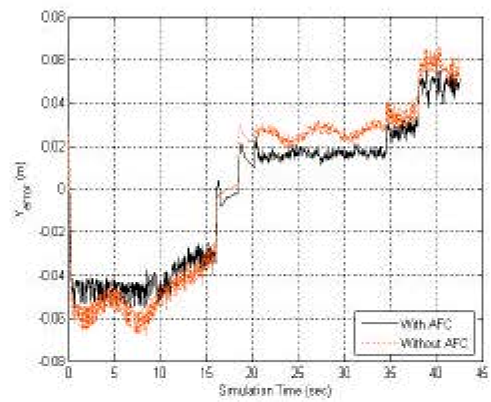

Fig. 9: Track error for y

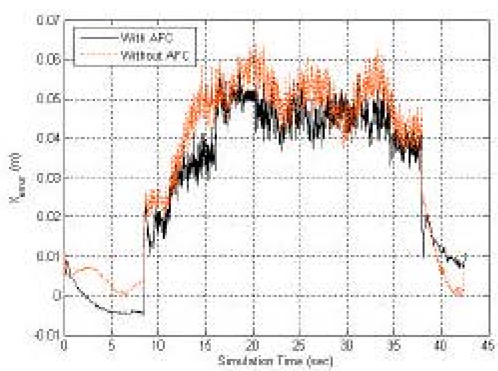

Fig. 8: Track error for x

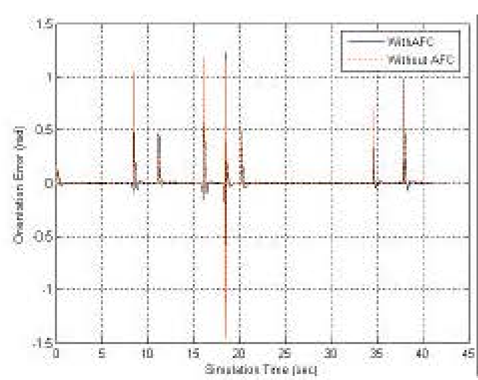

Fig. 10: Track error for ϕ

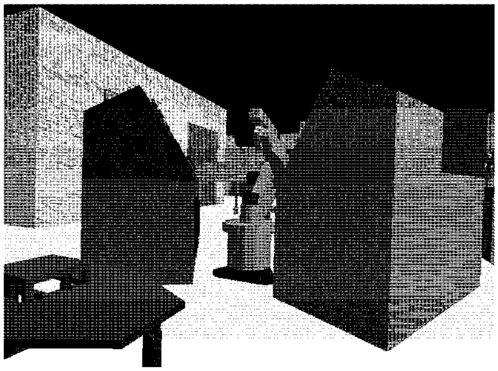

Fig. 11: Side view of WMR

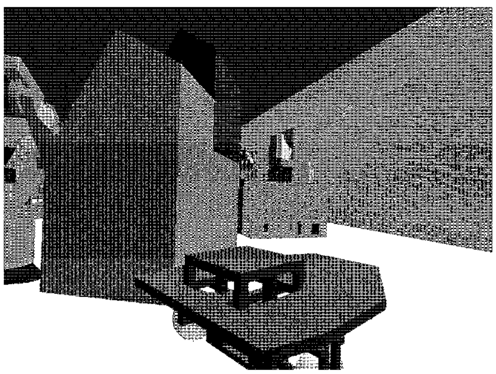

Fig. 12: Side view of WMR

curves by the RAC only controller as depicted in Fig. 8 and 9. Thus, it is clear that without AFC, the motion controller was unable to accommodate the presence of the externally applied disturbances. In other words, the controller failed to generate counter reacting torques at the actuators (motors) to facilitate the said disturbances. In summary, it is very obvious that the RAC with AFC scheme produces superior trajectory tracking performance due to its robust control action.

Figure 11 to 14 shows the snapshots of the scene rendering during the simulation. Essentially, the snapshots were in fact graphical extracts from the actual animation of the system in which the WMR with the proposed control algorithms is shown to navigate cleverly within the CIM layout without hitting the obstacles along its path. Apart from providing the rich graphical representation of the WMR and its environment, the virtual simulator also helps researchers to enhance their knowledge and understanding of the effects of the physical layouts, workspace and others on the actual performance of the WMR. The obtained information may be of use for future physical experimentation setup.

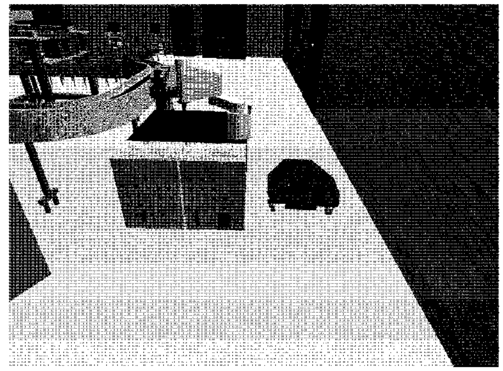

Fig. 13: A bird's eye view of WMR

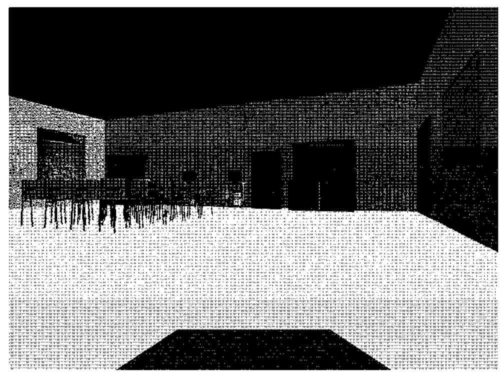

Fig. 14: First person view of WMR

CONCLUSION

The WMR simulator has been successfully designed and developed as a testbed for the experimentation of control algorithms applied to WMR in a CIM setting environment. It is observed that the WMR is able to plan for a global collision-free path which is then transformed into the time-indexed trajectory through the proposed trajectory planner. With this generated trajectory, the proposed motion controller is able to drive the virtual WMR to track the reference path towards its destination target autonomously without colliding with the obstacles in its path even though it is subject to a number of introduced disturbances. The RAC with AFC scheme is found to be much more effective and robust compared to the RAC only counterpart in generating the compensation torques that are required for the cancellation (rejection) of the disturbance torques. The direct consequence of the use of the virtual WMR is that it provides a useful platform for the design of actual WMR control system. This may lead to reduction in the actual experimentation time and cost while at the same time providing greater insight into the performance of the robot control algorithms as the WMR can be directly and graphically observed via the simulator. Future direction may include the more immersive nature of the simulator with different operating and loading conditions.

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