A Haptic-Assisted Guidance System For Working Machines Based on Virtual Force Fields

Simone Patrinostro, Matteo Tanzini, Massimo Satler
Emanuele Ruffaldi, Alessandro Filippeschi, Carlo Alberto Avizzano
PERCRO - Scuola Superiore Sant'Anna, Pisa, Italy

Email: simone.patrinostro@gmail.com; m.tanzini@sssup.it; m.satler@sssup.it; e.ruffaldi@sssup.it; a.filippeschi@sssup.it; c.avizzano@sssup.it;

***Abstract*—This paper presents a new approach to improve the remote navigation of a teleoperated demolition machine. To improve navigation usability of the teleoperated system the following topics will be covered: obstacle avoidance, wall alignment, and machine optimal positioning for demolition operations. In order to enhance the ability of the operator to navigate in a cluttered environment, a Haptic-Assisted Guidance System(HAGS) will be introduced. HAGS is a guidance system based on haptic simulation which improves the awareness of the operator on the surrounding environment. The solution proposed has been tested using a virtual environment scenario and a commercial Haptic interface, the results have been analyzed and discussed.**

***Index Terms*—Haptic, Guidance, Human-in-the-loop, Human-Machine-Interface, Obstacle Avoidance, Force Feedback, Teleoperation, Working Machines**

I. Introduction

One of the current challenges in the field of robotics is to create working machines that are more and more independent. However, considering the state of art of modern robotics technology, fully autonomous systems can not yet be the answer for every type of activity. In fact, humans possess unmatched characteristics regarding reaction times, reasoning and decision-making abilities of unforeseen situations. Therefore, try to improve the performances of human operators, reducing the risks, become a valuable improvement.

One of the main topics which must be taken into account in the design of a working machine is the type of working environment (typically unstructured). In order to prevent accidents, improve safety and productivity, the machine operator must follow a long period of training. Usually working machine tasks include a certain type of risks, especially if the task comprehends demolition and navigation in a very cluttered environment, so the operator should be very familiar with the environment in which he operates.

In the last decade, companies such as Husqvarna, Brokk and Finmac introduced tele-operated demolition machines (Fig. 1). These machines are of different size and power and rely on the presence of an operator nearby. Through a wearable console, composed of a series of levers and joysticks, the operator has the possibility to maneuver the nonholonomic machine but has no feedback during the operation but visual.

This paper propose new interaction models, for demolition working machines that can interact with the operator, in order to make their guidance easier, thus increasing their safety and productivity.

Fig. 1: An operator driving a Brokk demolition working machine. The controller interface is shown bottom right.

One of the most important factors while driving a vehicle is the comprehension of the workplace (Fig. 2a), where the machine is located and navigates. This aspect is important to allow the operator to drive the vehicle safely avoiding possible impacts with the environment.

In addition, the comprehension of the workspace of the machine's arm, are fundamental to be able to place the mobile base in the best position before arm operation, consequently, to perform the arm movements in the most effective way. An example of a typical task that the machine may have to do, is to perform a trace on a wall (Fig. 2b): this task involves both navigation and manipulation. For example, placing the mobile base of the vehicle in an improper position, brings a harder (if not impossible) manipulation. The operator will have to reposition the machine, slowing or interrupting the manipulation, resulting in a loss of time and lower productivity.

Another typical demolition task is to operate along a wall, for example performing a straight trace on a long wall. This implies a frequent navigation side by side to a wall. In this type of navigation, unlike standard navigation, obstacles (in this case the wall itself) are seen as working areas. Our system helps the operator to maintain the robot aligned to the wall as to avoid collision with the same, in order to improve the performance of the combined operation. In Fig. 2c an example of combined operation is shown, here the operator drives simultaneously the mobile base and the arm together.

This paper aims to introduce a new methodology to improve the security and the performances of demolition working machine's operators through the use of haptic and robotic features, the detailed description is organized as follows. Section II presents a short overview of the current state of the art on Haptic Assisted Guidance Systems. Section III describes the proposed approach and its implementation. Section IV describes the architecture and software components of the testing system. Preliminary test sessions and results are presented and discussed in section V. Finally conclusions are drawn in section VI.

(a) (b)

(c)

Fig. 2: Typical tasks in a demolition environment: (a) driving in narrow areas; (b) making a trace on a wall; (c) driving the demoliting arm and the mobile platform combined.

II. Related Work

We can find many examples on haptic guidance of Unmanned Ground Vehicles (UGV) in literature, but few address the problem of manipulation and navigation combined, especially considering specific task as demolition. Several important aspects are considered: the nonholonomic constraint of the mobile robot, command strategy [7], [6], haptic rendering [8], obstacle avoidance.

Nowadays, in the field of demolition, we can find several proposals for new types of human-machine interaction, Tanzini et al. in [16] propose a new interaction methodology to drive a demolition arm, by projecting the arm path on the target wall with a compact projector.

Even to this day, it is challenging to consider the actual shape of a vehicle implementing 2D obstacle avoidance algorithms. Many articles approximate the shape of the vehicle with a simple circle. This kind of approximation is not suitable for vehicles with a complex polygon shape, it could take to unexpected collisions in tight spaces.

Melchiorri et al. [5] propose a teleoperation system that allows the operator to drive a nonholonomic robot through haptic device.

Kondo et al. in [11] approximate the shape of the vehicle analyzed with an ellipsoid, instead of a circle, to allow navigation in narrow areas. A rectangular shape is also considered in [12], [15].

Hou et al. in [10] construct a Dynamic Kinesthetic Boundary (DKB) on the master device workspace providing the pilot hard boundaries in the haptic workspace to indicate approaching obstacles.

In relation to optimal positioning of a robotic arm in front of a specified task, Asokan et.al [2] and Abdel et al. [1], introduce a new method to calculate boundary and singularity surface of the workspace.

Haptic stimuli are widely and succesfully used in different fields of applications, as the rehabilitation robotics in [3].

III. Novel Haptic-Assisted Guidance System

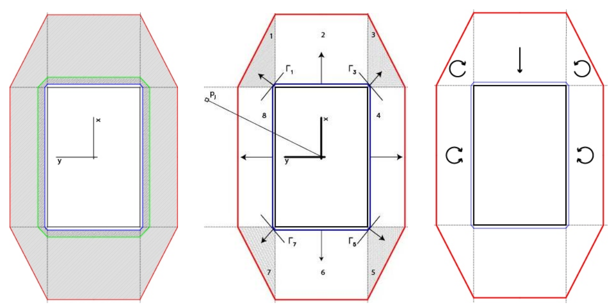
In this section we propose three new navigation modes for:
- *Standard Navigation*
- *Optimal Positioning*
- *Coastal Navigation*

Furthermore an additional mode, referred to as "comprehension workspace", has been developed to increase awareness of the operator during the positioning task.

A. Standard Navigation

The standard Navigation Mode aims to improve the safety of the vehicle and the user during navigation through a cluttered environment. The new interaction mode informs the operator on the surrounding environment through a variable haptic feedback.

We define two virtual regions around the vehicle (represented by the black border in Fig. 3a). A "free motion" region (between red and blue lines), here obstacles are identified and reflected to the user using a haptic feedback. A critical region (between green and blue line), an obstacle identified in this region will make the navigation stop, to avoid collision.



(a) (b) (c)

Fig. 3: (a) Definition of the main observation regions; (b) Observation region subsections; (c) Haptic rendering (forward motion case).

The analyzed area around the vehicle is splitted in eigth zones (Fig. 3b): front, rear, sides and angular zones. During navigation we consider all the obstacles in the observation region but react just to the closest obstacle of each region, which are the biggest threat. The presence of obstacles in each region will be felt by the user through the haptic device combining the effect of each obstacle treated. The distance between an obstacle and the vehicle is considered to be the minimum distance R_i between the obstacle p_j and the segment (or his projection) (Fig. 3b) which belongs to the same zone. Γ_i $i = 1, \ldots, 8$ defines each segment that compose the blue polygon.

To enhance the capabilities of the system to consider obstacles along the cruising direction, we decided to use a deformable Free Region that dynamically stretches or shortens the boundary of his zones in front of the navigation's heading. The red boundary changes according to the navigation vector in order to "see" farther in the direction in which we are heading. The deformation is proportional to the vehicle speed.

The distance R_i is inversely proportional to the force reflected to the user through the haptic device. The haptic force direction is represented in Fig. 3c. Basically an obstacle identified in the front zone creates an opposing force to the one applied by the user to the interface to increase the forward speed of the vehicle, while angular zones 1 and 3 oppose to the force applied for the rotation in order to turn away from obstacles. Side zones 4 and 8 generate forces like zones 1 and 3, however the distance between the obstacle and the base is considered, in order to not generate a collission during the suggested rotation of the vehicle.

The function that relates the distance of the obstacle to the force feedback is made of three linear traits (Fig. 4). The distance R is the minimum distance from an obstacle. Obstacles over the distance Th_3 will be not perceived from the user while obstacles before the distance Th_1 generate a force on the user haptic interface that will not allow further movements. Inside these two borderline cases two linear profiles has been chosen: one to amplify the force generated from far obstacles and one to smooth strong forces generated by the closer ones. These profile has been created to ease the operator guidance.

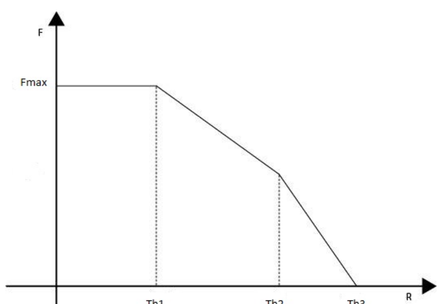


Fig. 4: Standard Navigation force profile.

B. Optimal Positioning

This mode aim to help the operator to find and reach the best position before operating with the vehicle robotic arm. We assume that the operator task consist in trace a straight line on a wall. The operator can show the trajectory to the system specifying two target points which represent the start and end point of the trajectory. The goal for this type of task is having the robot in the best position in terms of dexterous manipulation [18] to complete the trace on the wall. To fulfil this objectives we addressed two problems: find the optimal position of the robot and define a haptic assistance to help the operator moving robot to the position found.

The first problem has been addressed taking in consideration the arm's workspace geometry, the target points, any obstacles in the environment. At last, at the optimum location, the robot should satisfy several conditions:

1) none of the target points should lie on the manipulator singular surfaces,
2) target points should lie within the manipulator workspace,
3) there should be no obstacles in the optimum location.

The boundary and the singularity surface of the five degrees of freedom (DOF) Kuka youBot arm are analytically determined using the method presented by Abdel et al. [1] and properly adopted. In detail, we have introduced two additional constraints to verify that the optimal position to reach is not occupied by any obstacle

$$\frac{b}{2} - |(d_r - P)\,\mathbf{i}| \leq 0 \tag{1}$$

$$\frac{a}{2} - |(d_r - P)\,\mathbf{j}| \leq 0 \tag{2}$$

where a and b are respectively the width and length of the vehicle, P represents the position of the vehicle, **i** and **j** are versors of the frame *basic_link* fixed with the vehicle, while d_r represents the *r-th* obstacle respect navigation frame. Indeed, we maximized the following cost function to improve dexterity at specified target points, based on Yoshikawa manipulability index [17]

$$\sum_{l=1}^{2} \omega_l \sqrt{det(J(q)\,J(q)^T)} - \left\|P^{(m)} - P\right\|_2 \tag{3}$$

where we denoted by $P^{(m)}$ target midpoint respect navigation frame, $J(q)$ youBot arm Jacobian, ω_l an arbitrary weight and with l the number of target points.

Finally, we obtain the optimal position w^* used for the haptic rendering. We have developed two force fields denoted as M_1 and M_2 to help the operator to place the vehicle as close as possible to the optimal position calculated. The force field M_1 is constituted by a forward force and a force proportional to heading error that guides the operator to the optimal position

$$F_x \propto \left\|w_p^* - P_a\right\|_2 \tag{4}$$

$$F_y \propto |w_\gamma - \gamma| \tag{5}$$

Where w_p^* and w_γ represent the optimal position and orientation to reach.

While, the force field M_2 is based on haptic stimuli to inform the operator how far is the vehicle with respect to the optimal position to reach. In fact, we use two signals, with variable frequency, to send the operator two type of information: the position error and orientation error. The frequency of these stimuli is proportional to the error amplitude. In this way, the operator can position the vehicle more accurately without excessive stresses due to the stimuli at high frequencies.

C. Coastal Navigation

In this navigation mode, the operator is supposed to drive the vehicle along a sidewall. The pilot is supposed to receive haptic stimuli with the aim to keep the vehicle aligned with the wall. During a coastal navigation the operator is supposed to drive close to a wall with reduced speed in comparison to the standard navigation mode. Due to this limitations the observation region has been reduced to allow a comfortable navigation.

In this modality the operator canrequest assistance to the system to ease the alignment of the vehicle to front or sidewalls. The vehicle is properly aligned when the sides of the vehicle and the wall are parallel to each other. The profile of the wall is identified by two points obstacle located at the extremes of the frontal zone (case alignment with respect to the front wall) and approximated by a straight line. We can then easily calculate the orientation error $\tilde{\theta}$ between the profile of the wall and the orientation of the vehicle. We proposed two force fields (both adjustable by the constants $Th_{1,2,3}$, $S_{1,2,3}$ and α), the first C_1 (6) composed of linear section

$$C_1 = \begin{cases} 0 & 0 \leq \tilde{\theta} \leq Th_1 \\ (\frac{S_1}{Th_2 - Th_1})\,(\tilde{\theta} - Th_1) & Th_1 < \tilde{\theta} \leq Th_2 \\ S_1 & \tilde{\theta} > Th_2 \end{cases} \tag{6}$$

and a force field C_2 (7) composed of linear and concave sections.

$$C_2 = \begin{cases} 0 & 0 \leq \tilde{\theta} \leq Th_1 \\ \alpha\sqrt{\left|\tilde{\theta} - Th_1\right|} & Th_1 < \tilde{\theta} \leq Th_2 \\ S_1 + (\frac{S_2 - S_1}{Th_3 - Th_2})\,(\tilde{\theta} - Th_1) & Th_2 < \tilde{\theta} \leq Th_3 \\ S_2 & \tilde{\theta} > Th_3 \end{cases} \tag{7}$$

The force profile C_2 is composed by a first concave section to help the operator to correct the alignment in a smoothest way respect to profile C_1.

D. Comprhension Workspace

Simultaneously in the navigation mode we want to keep informing the operator on the geometries of the workspace of the arm. This was accomplished by sending the operator a further haptic stimulus, in the form of a short oscillation, when a target point enters the working space reachable by the arm. This additional stimulus allows the operator to position the vehicle more easily.

IV. System Architecture

This section introduces the architecture of the system used in order to assess the new HAGS. The testing system developed provides a simulator where the user is supposed to drive a simulated vehicle in a virtual environment through a haptic interface. The simulation will be displayed to the pilot through a standard PC monitor.

The software consists of five main components. The ROS framework has been chosen to be the platform to integrates several software components of the system [14]. It provides hardware abstraction, libraries, obstacles map, visualizers, message-passing, package management, and more.

We have chosen the Kuka Youbot as a reference testing platform [4], since its structure (a mobile base with a anthropomorphous arm) is comparable to a typical demolition working machine, once used as a nonholonomic vehicle.

The haptic interface used is the Novint Falcon [13], managed by the open source libraries libnifalcon.

To ease the software development, the navigation modes have been developed in Matlab using the Robotic System Toolbox of MathWorks that already provides the possibility of information exchange with ROS.

The software V-Rep [9] has been chosen as simulation platform. It provides the possibility to simulate the Youbot platform and make it interact with a ad-hoc virtual environment. Moreover the simulation platform provides different sensors for obstacle avoidance integrable with the simulated robot.

V. Preliminary Test Session

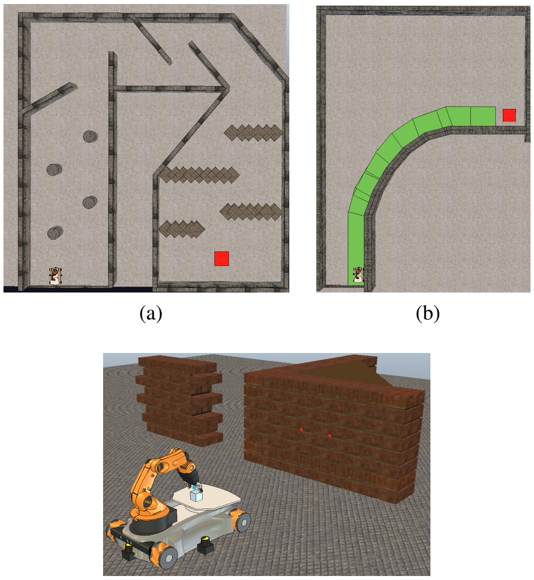
Preliminary tests have been carried out to test how our system could constitute a valuable help for operators. In the present case, experiments in three different virtual environments (Fig. 5) were performed, to measure the effectiveness of the navigation modalities implemented to improve safe navigation and usability. For each of the navigation modes developed (standard, coastal and optimal) an ad-hoc virtual environment was created in which the participants have to perform a specific task.

9 subjects (aged 20 to 40) participated in the experiment (duration 20 minutes). The participants, through the haptic interface, are able to generate the commands to forward speed and yaw rate of the robot. Each participant is first subjected to a learning phase. After, they perform three experiments, each of which expect the repetition of the same with different force feedback profiles(Table I).

Experiment	**Trial**	**ID**	**Navigation Mode**
Experiment 1	No force feedback	T1	Standard
	with force feedback	T2	
Experiment 2	No force feedback	T3	Optimal Positioning
	M1 profile	T4	
	M2 profile	T5	
Experiment 3	No force feedback	T6	Coastal
	C1 profile	T7	
	C2 profile	T8	

Table I: Summary of the experiments performed for each participant.

A. Experimental Scenarios



(a) (b) (c)

Fig. 5: The virtual environments used for experiments.

1) *Standard Navigation* (Fig. 5a): In this experiment two different methods of force rendering were tested and compared. Participants must drive the vehicle from the initial position (bottom left in figure) until they arrive at the finish goal (bottom right in figure), represented by a red square (Fig. 5a), trying to keep the vehicle away from obstacles and at the same time reach the destination in the shortest time.
2) *Optimal Positioning* (Fig. 5c): Participants are asked to place the vehicle correctly to make a trace on the wall. The start and end point of the trajectory are represented in Fig. 5c with two red spheres. In order to find which haptic feedback helps most the operator to place the vehicle in the best position, the user is supposed to repeat the same scenario with three different force feedback: without, profile M_1 and profile M_2. M_1 and M_2 profiles helps the user to drive the robot using the force feedback. The best position is pre-calculated by the system as in Section IIIB.
3) *Coastal Navigation* (Fig. 5b): Participants are asked to drive the vehicle along a wall without hitting it. The green rectangles represent the region near the wall in which the vehicle is supposed to navigate. In order to find the best haptic rendering, three different profiles were tested and compared: no force feedback, profile C_1 and profile C_2.

The Next sections aim to analyze the results of the testing session.

B. Results Experiment Standard Navigation

This mode has been evaluated through three indices of performance: completion time of the task, overall distance traveled and number of collision with the environment along the route. The respective indices are represented graphically by a box-plot, each figure shows different modes results for the same test. Fig. 8 shows the collisions for both modes. It's possible to observe, that participants are able to reach the goal with a remarkable lower number of collisions, through the force feedback navigation. Indeed, without force feedback, more than 50% of the participants collide with the environment. However, there was no significant difference on navigation time (Fig. 6) and on distance traveled (Fig. 7).

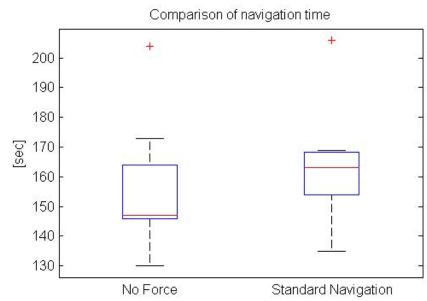


Fig. 6: Standard Navigation: navigation time.

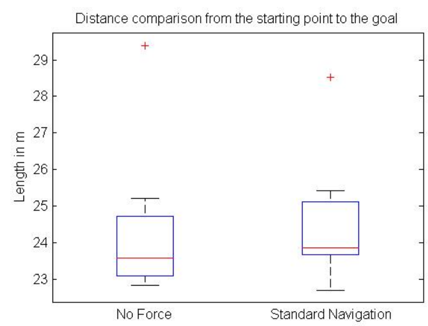


Fig. 7: Standard Navigation: distance traveled.

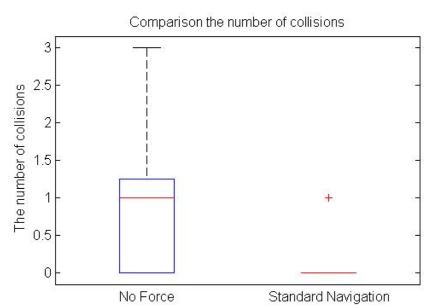


Fig. 8: Standard Navigation: number of collisions.

C. Results Experiment Optimal Positioning

We compared the haptic stimuli to assess performance during positioning task. Fig. 9 and Fig. 10 show, rispectively position and orientation error between vehicle and desired position. Both errors were reduced through haptic feedback developed. Best results were obtained using force feedback based on stimuli (Profile M_2). In this case, the position to reach is transmitted through haptic stimuli that allow to better identify the correct actions to be imparted to the vehicle.

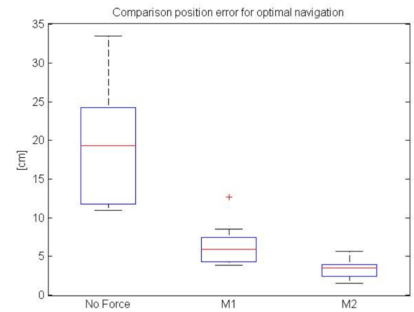


Fig. 9: Optimal Positioning: position error.

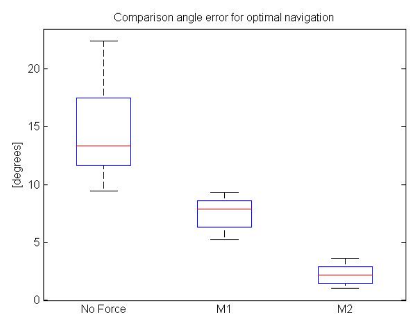


Fig. 10: Optimal Positioning: angle error.

D. Results Experiment Coastal Navigation

Fig. 11 shows the orientation error between vehicle and wall using different feedback profiles. Without force feedback the subjects make an error of orientation higher compared to the other tests, while the best performance was obtained with the profile C_2.

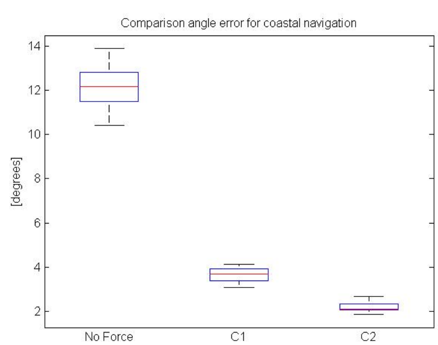


Fig. 11: Coastal Navigation: alignment error.

VI. Conclusion and Further Works

This paper presented a new haptic guidance system capable of improving the typical activities of a demolition working machine. Our system help the operator in navigation, wall-follow and optimal positioning tasks through haptic cues. A preliminary test session has shown an improvement in performance in terms of accuracy and safety during navigation. Further investigations expect to test the system on a real demolition working machine.

References

[1] Karim Abdel-Malek, Wei Yu, and Jingzhou Yang. Placement of robot manipulators to maximize dexterity. *International Journal of Robotics and Automation*, 19(1):6–14, 2004.

[2] T Asokan, G Seet, M Lau, and E Low. Optimum positioning of an underwater intervention robot to maximise workspace manipulability. *Mechatronics*, 15(6):747–766, 2005.

[3] CA Avizzano, M Satler, G Cappiello, A Scoglio, E Ruffaldi, and M Bergamasco. Motore: A mobile haptic interface for neuro-rehabilitation. In *RO-MAN, 2011 IEEE*, pages 383–388. IEEE, 2011.

[4] R Bischoff. Kuka youbot–a milestone for education and research in mobile manipulation. In *IEEE ICRA Workshop–A New Generation of Educational Robots. KUKA Laboratories GmbH, Shanghai International Convention Center, Augsburg, China*, volume 76, 2011.

[5] Nicola Diolaiti and Claudio Melchiorri. Haptic tele-operation of a mobile robot. In *Robot Control 2003 (SYROCO'03): A Proceedings Volume from the 7th IFAC Symposium, Wrocław, Poland, 1-3 September 2003*, volume 1, page 7. Gulf Professional Publishing, 2004.

[6] Ildar Farkhatdinov and Jee-Hwan Ryu. Hybrid position-position and position-speed command strategy for the bilateral teleoperation of a mobile robot. In *Control, Automation and Systems, 2007. ICCAS'07. International Conference on*, pages 2442–2447. IEEE, 2007.

[7] Ildar Farkhatdinov and Jee-Hwan Ryu. A user study of a mobile robot teleoperation. In *Proc. of the 4th International Conference on Ubiquitous Robots and Ambient Intelligence*. Citeseer, 2007.

[8] Ildar Farkhatdinov, Jee-Hwan Ryu, and Jinung An. A preliminary experimental study on haptic teleoperation of mobile robot with variable force feedback gain. In *Haptics Symposium, 2010 IEEE*, pages 251–256. IEEE, 2010.

[9] Marc Freese, Surya Singh, Fumio Ozaki, and Nobuto Matsuhira. Virtual robot experimentation platform v-rep: a versatile 3d robot simulator. In *Simulation, Modeling, and Programming for Autonomous Robots*, pages 51–62. Springer, 2010.

[10] Xiaolei Hou and Robert Mahony. Dynamic kinesthetic boundary for haptic teleoperation of aerial robotic vehicles. In *Intelligent Robots and Systems (IROS), 2013 IEEE/RSJ International Conference on*, pages 4549–4950. IEEE, 2013.

[11] Yasumasa Kondo, Takanori Miyoshi, Kazuhiko Terashima, and Hideo Kitagawa. Navigation guidance control using haptic feedback for obstacle avoidance of omni-directional wheelchair. In *Haptic interfaces for virtual environment and teleoperator systems, 2008. haptics 2008. symposium on*, pages 437–444. IEEE, 2008.

[12] Sangyoon Lee, Gaurav Sukhatme, Gerard Jounghyun Kim, and Chan-Mo Park. Haptic teleoperation of a mobile robot: a user study. *Presence: Teleoperators and Virtual Environments*, 14(3):345–365, 2005.

[13] Steven Martin and Nick Hillier. Characterisation of the novint falcon haptic device for application as a robot manipulator. In *Australasian Conference on Robotics and Automation (ACRA)*, pages 291–292. Citeseer, 2009.

[14] Morgan Quigley, Ken Conley, Brian Gerkey, Josh Faust, Tully Foote, Jeremy Leibs, Rob Wheeler, and Andrew Y Ng. Ros: an open-source robot operating system. In *ICRA workshop on open source software*, volume 3, page 5, 2009.

[15] Hiroaki Seki, Yoshitsugu Kamiya, and Masatoshi Hikizu. Real-time obstacle avoidance using potential field for a nonholonomic vehicle. *Factory Automation*, pages 523–542, 2010.

[16] Matteo Tanzini, Paolo Tripicchio, Emanuele Ruffaldi, Guido Galgani, Giovanni Lutzemberger, and Carlo Alberto Avizzano. A novel human-machine interface for working machines operation. In *RO-MAN, 2013 IEEE*, pages 744–750. IEEE, 2013.

[17] Tsuneo Yoshikawa. Manipulability and redundancy control of robotic mechanisms. In *Robotics and Automation. Proceedings. 1985 IEEE International Conference on*, volume 2, pages 1004–1009. IEEE, 1985.

[18] Leon Zlajpah. Dexterity measures for optimal path control of redundant manipulators. In *Proceedings of International Conference on Automatisation and Control (ICAR)*. Citeseer, 1996.