Modular Intelligent Interface to Assist Human in Operating Construction Machines(建設機械の操作における人間支援のためのモジュール型知的インターフェースに関する研究)

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論　文　内　容　要　旨

Chapter 1: Introduction

We defined here our field of investigation for this thesis. We have seen that it exists many different kinds of machines to accomplish numerous kinds of tasks, and sorted them into four kind of work using the hydraulic arm with a tool to engage the terrain and displace soil, or a tool to grip and crush, or a special tool to perform a specific task (like a concrete injection nozzle), or a tool as a platform to allow the operator to approach an unreachable spot. Then, we provided some basics about how to control those construction machines using concepts coming straight from the robotic telemanipulation field, and briefly presented the direct joint control, the manual teleoperation, and the semi/fully automated teleoperation. After talking about the related works of Nakano et al., for the proposed architecture, we detailed the assumptions made. We focused on the modularity of the system, in order to let the human operator having an optimal control of the task to accomplish, letting the machine handling the low-level control, the repetitive and highly mentally demanding presence. In this thesis we focused more on the way the intelligent interface handles the high-level control provided by the operator, and discussed about the degree of autonomy of the machine, and did not consider the already well studied field of low-level control policy that manages the cylinder length, speed or motor torques depending on the dynamic of the manipulator. To finish with Chapter 1, we described the report structure.

Chapter 2: State-Of-The-Art of the solutions using robotic in civil engineering

We made a short survey of the techniques used in this field to assure the cycle of autonomous machines: *sense*, *plan*, and *execute*. The survey of sensing techniques presented the three classes of sensing technologies that allows the machine to determine its own state, to determine its environment, and the perceptual feedback provided to the remote operator. Then, we examined models of mechanisms that are used for machine design and to construct laws that relate sensed quantities to actuation. We briefly described the kinematics models that deal with geometry and speed relationship between the end effector position, orientation and speed, and parameters at each joint, and the dynamic model that is encoding relationships of quantities such as mass, friction, etc., to accelerate bodies. To conclude with this chapter, we proposed a survey of some teleoperated system using retrofitted and non-retrofitted hydraulic manipulators. We showed that most of the retrofitted systems are using a classical master-slave approach that sometimes is bilateral to reflect some forces applied onto the tool of the slave manipulator into the hand of the operator. While the retrofitted machine are using systems to allow the remote operator to interact directly with the work-site, the non-retrofitted machine system are interfaces between the remote operator and the on-board system of levers of the construction machine. To do so, non-retrofitted system are using humanoid teleoperated robots, or teleoperated actuators with human sizes to fit into the ``designed for human" construction machine.

Chapter 3: To an Intelligent Interface

This chapter was aiming to detail the philosophy that lead to our concept of intelligent interface. We first presented some examples of work done with industrial vehicles, in order to demonstrate that the current way those vehicles are controlled needs of manoeuvrability enhancement to cope with the complex system of levers, and needs to deal better with the diversity of the machines and tasks. It showed that in the previous survey of Chapter 2, all the systems were considering only the manoeuvrability enhancement (retrofitted machines) or the diversity of machines and task (non retrofitted machines), but never both of them. This analysis leads us to define designing criteria for the Intelligent interface. After presenting the concept of supervisory control, and analyzing the criteria, we could choose the most adequate degree of autonomy for the intelligent interface, and proposed a new concept based on an intelligent interface in between the operator's manipulator and the target machine's one, that owns virtual images of the status of each manipulator. Those images are synchronized thanks to the implemented high-level control to define the next target to reach by the manipulators.

Chapter 4: A modular approach

Here we are aiming to present the implementation of this Intelligent Interface concept using a modular approach. We first provide some definition of the terms used to describe the system, and a basic overview of it. Then we made an analogy to the Computer Integrated Manufactory pyramid concept, to prepare the reader to get more precise description of the way the system is working, through the general class diagram of the system. The software implementation is composed of three separates processes, using a client-server application. The Brain process is the server process, that owns the virtual images of the manipulators' status, and the high-level control and manage synchronization of clients and the communication between them. The master and the brain processes are client applications that connect to the brain process through the (wireless) LAN to send the status of their attached manipulators. They are managing their low-level control as well. A module is a communicating process with an attached hardware (manipulator, 3-D simulation of a manipulator,...). Once this concept was clarified, we detailed the content of each implemented modules. Inside the Intelligent module that owns the brain process, each master and slave manipulators are represented by two images, the current images that represents the latest status of the manipulators, and the target images where are written the results of the high-level control computation. This target image of the manipulator is used by the intelligent module to send the new target to reach by the concerned manipulators. The mechanism to select the high-level control strategy and some of the implemented strategies are detailed as well. We developed two different control types (position and rate control) applicable to three different operating modes (joint, Cartesian and slope). One should notice that others can easily be implemented thanks to the object oriented and reusable architecture of the system. While the intelligent module owns the computer network, and the brain process, the slave and master modules own respectively the slave and the master manipulators, and their attached processes that are the drivers of those manipulators. We presented in detail the implemented master and slave modules using different real and virtual (i.e. simulation of) manipulators and visualization, in order to prove that the *intelligent interface improved the manoeuvrability and considered the diversity of the task and the machines*. To finish we showed a real example of topology and the way to define it through the processes options when starting the system.

Chapter 5: Kinematic models of the modules

Here is detailed the kinematic model used for each implemented modules. The two first sections are presenting global methods used to determine the forward and inverse kinematics of a serial robot. And the other sections detailed the specific models used for each implemented modules (master, slave, and camera tracking system).

Chapter 6: Advantages and applications of the proposed Platform

Here we are proposing some pertinent configurations for the Intelligent Interface, to be able to evaluate the proposed platform. The first proposed configuration is to realize a classical on-board task. This configuration is an application of the already largely investigated research concerning the manoeuvrability enhancement of the control of the construction machines by an operator inside the cockpit. An example of configuration using a 3-D interactive simulation of a 5 DOF excavator represents the slave manipulator, while the monolever developed by Nakano is used as the active haptic master manipulator. Some results concerning the tracking performances of the system can be found there. The second topology proposed concerns the remote teleoperation applications. The use of a virtual 5 DOF excavator equipped by a gripping tool, remotely control through the Intelligent Interface and through a wireless LAN, is controlled in different operating modes by an operator using a monolever. An experimental protocol has been decided where the remote operator is grabbing a cube and dropping it to a defined area. The time is measured in the different modes, and results are compared. The third proposed configuration's purpose is to be a test-bed of our system using a safer industrial manipulator PA10, equipped by a gripper tool. The experience consists in gripping a ball with a direct visual feedback of the work site, then with a global video feedback only, and finally with a global and local (tool) video feedback. The times to accomplish this task are compared to evaluate the three cases of visual feedback through the Intelligent Interface. The last example of possible configuration allowed ergonomic test and training of operator on simulators. Ergonomic tests using a 3-D interactive simulator can be done to evaluate the way of controlling a very expensive industrial vehicle like a bridge checker in total safety or a non available or non existent hydraulic machine like a two armed excavator. The test-bed can be used for training purposes and as well for control laws testing in perfect safety.

Chapter 7: Conclusion

This Chapter summarizes the content of the thesis, concludes and presents possible further investigation. Useful information concerning relation between cylinder parameters and joint angles one can be found in the Appendices pages with some information about the author.

The main contributions of this research are the following:

_ A new approach for the design of the controlling system of the hydraulic machines that deals either with manoeuvrability of the machines, and diversity of the tasks to do and machines configuration,

_ A multiplatform modular solution that allows several configurations for testing the control of machines, training operators on simulators, accomplishing a task remotely, and monitoring.

_ An open and well designed object oriented architecture for an easy implementation of new machines characteristics, with a normalized protocol of communication on an abstracted communication layer for an easy interoperability between the components of the system, and for an improvement of the productivity in development of new modules and simulators

The first point allows any private individuals or inexperienced professionals to perform difficult tasks that would require a well-trained operator and increase considerably the productivity of a professional. The second point allows civil engineering companies to be more flexible with their hardware and increase as well the global productivity and site management. The last point considerably increases the developers' productivity, by re-usability of the code and thanks to the standardized protocol of communication between the modules.

The superiority of our system on the other surveyed one is that its open modular architecture allows the use of any hydraulic machine, and the possible configurations allows training, simulation, testbed for control and ergonomics, remote work over the Internet or a (wireless) local area network. The flexibility allowed by the Intelligent Interface does not exist for most of the surveyed solutions and therefore allows productivity gains.

論文審査の結果の要旨

本論文は、建設現場におけるさまざまな種類の機械や作業に対して有効な人間操縦環境を構築するために、人間操作部、制御部、作業機械部を電気信号的にモジュール化することで、各部の汎用性と操作性を向上する方法を提案し、その有効性を論じるものである。併せて、遠隔操縦における遠隔臨場感の向上を目指して、力覚のフィードバックとともに三次元リアルタイムシミュレータ並びに遠隔視カメラの使用と操作を可能とするインテリジェントインタフェースを構築する手法について論じるもので、全編７章より成る。

第１章は序論で、本論文で取り扱う建設作業と建設機械の問題点について述べている。一般に建設機械を用いての精密作業では高度な熟練とオペレータの微妙な操作感を要するため、特に遠隔での無人化施工に困難と効率の悪さが生じている現況について述べている。

第２章では、建設作業にロボットを導入することで問題点の解決に当たろうとする研究開発の先端事例を挙げ、そこにおける問題点を指摘するとともに、本論文で取り扱う手法の根幹をなす理論的な部分について記述している。次いで、本論文の主題であるインテリジェントインタフェースの概念を記述している。すなわち、オペレータによる建設機械本体の操作を従来の各自由度別個制御によるものから、オペレータの操作時の直感に適合し、しかも片手で基本操作が可能なモノレバー操作装置を用い、どこにいようともオペレータの現在の作業機械の形状をあらゆる角度から見ることの出来るリアルタイム３次元シミュレータ、並びに遠隔テレビカメラによるテレビ画面を通じての目視、などを総合的に合わせた操作システムを可能とするインテリジェントインタフェースの概要について記述している。

第３章では、操作装置及び作業機械がそれぞれ異なる形状をしていても必要な情報伝達が可能となる基本アイデアである各モジュールでの３次元直交座標系への情報変換について記述するとともに、建設現場での作業におけるその有効性を確認している。

第４章では、モジュール化手法に基づく基本アイデアの実現方法について、電子回路及びモジュール間交換情報の内容の詳細を記述しているとともに、その実装方法について述べている。

第５章では、モジュール間での情報交換を可能とする情報変換手法について、数学的記述により詳しく述べている。特に油圧ショベルの場合、作業に応じて関節モード、直交座標モード、斜面 (直線) モードを適宜切り替えて使うこととなるが、そのときの座標変換の具体例を数式表現を含めて詳細に述べている。

第６章では、具体的作業での適切なモジュール構成例とそれによる実験環境について述べ、さらに地上の対象物を作業装置のグリップ部に搭載されたテレビカメラ映像を遠隔画面で見ながらつかみあげる作業を例にとってその使用感と評価を行っている。オペレータによる両手を使った総合遠隔模擬操作はこれまで行われたことがないなど、建設現場における問題の解決に向かう可能性を示し得たことはたいへん有意義である。

第７章では結論と今後の課題を述べている。

以上要するに本論文は、建設現場における大きな課題の一つである要熟練作業の非熟練化、遠隔無人施工における臨場感の高質化と省人化を同時に可能とする手法をモジュール化というアイデアを基に総合的に論じたもので、情報科学及び工学の発展に寄与するところが少なくない。

よって、本論文は博士（情報科学）の学位論文として合格と認める。