AUTONOMOUS MATERIALS HANDLING ROBOT FOR ADVANCED MANUFACTURING APPLICATIONS

AUTONOMICZNY ROBOT DO TRANSPORTU I PODAWANIA MATERIAŁU W ZAAWANSOWANYCH APLIKACJACH PRODUKCYJNYCH

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Abstract: There is a need for mobile robots in reconfigurable manufacturing systems to reduce bottlenecks that occur in associated materials handling systems. These bottlenecks can occur as a result of the mass production of custom products. The project has focused on researching, designing, assembling, testing and validating a two-wheeled autonomous materials handling robot for reconfigurable manufacturing systems. A Mechatronic engineering approach, (system integration), has been used for the project. The approach required a vehicle that was dynamically and statically stable while in operation. Research has been done to obtain the optimum control strategy for the purpose of keeping the robot balanced for variable load characteristics. A navigation system has been researched that will allow the vehicle to perform materials handling tasks necessary to reduce bottlenecks. A wireless communication system has also been incorporated into the infrastructure of the vehicle. Performance analysis and testing in a reconfigurable production environment proves the viability of the materials handling system. This involves vehicle scheduling and routing while performing materials handling tasks.

Keywords: Manufacturing, Materials handling, Robotics.

Streszczenie: W rekonfigurowalnych systemach produkcyjnych istnieje zapotrzebowanie na zastosowanie mobilnych robotów pozwalających na złagodzenie problemów „wąskich gardeł”, które występują w skojarzonych systemach transportu i podawania materiałów. Takie wąskie gardła mogą wystąpić również podczas masowej produkcji wyrobów powszechnego użytku. Omawiane przedsięwzięcie było ukierunkowane na badania, projektowanie, montaż, testowanie i walidację dwukołowego autonomicznego robota do transportu i podawania materiałów stosowanego w rekonfigurowalnych systemach produkcyjnych. Dla potrzeb tego przedsięwzięcia zastosowano podejście inżynierii mechatronicznej (integracja systemu). Takie podejście wymagało użycia urządzenia jezdznego, które byłoby dynamicznie i statycznie stabilne w trakcie działania. Przeprowadzono badania ukierunkowane na uzyskanie optymalnej strategii sterowania, pozwalającej na utrzymanie robota w równowadze przy zmiennych charakterystykach obciążenia. Poszukiwano też takiego systemu nawigacji, który pozwoli pojazdowi wykonywać zadania związane z transportem i podawaniem materiałów, niezbędne do zmniejszenia uciążliwości „wąskich gardeł”. Do infrastruktury pojazdu włączono również bezprzewodowy system łączności. Analiza parametrów eksploatacyjnych oraz testowanie w rekonfigurowalnym środowisku produkcyjnym udowodniły przydatność systemu do transportu i podawania materiałów. Te badania obejmowały opracowanie harmonogramów czasowych i tras ruchu pojazdu podczas wykonywania zadań związanych z zadaniami transportu i podawania materiałów.

Słowa kluczowe: Produkcja, transport i podawanie materiałów, robotyka.

1. Introduction

The demand for customised products in the manufacturing industry is becoming more and more wide spread as customers have divergent needs and wants. Customisation of products means that products consist of different parts, and subassemblies. These parts can require different machining processes. Thus the final product may require variation in machining processes as well as variation in assembly processes. All of these variations cause variations in part flows in the manufacturing plant, which in turn can cause bottlenecks in these part flows. This is a result of the fact that some machining processes take more time than others and this causes parts that do not need to undergo these longer processes to be held up in the manufacturing line. One possible solution to this problem is the application of mobile materials handling robots to intervene in the line and transport the waiting parts to their next destination. These mobile robots could either assist a traditional conveyor based materials handling system or an Automated Guided Vehicle (AGV) based materials handling system.

A new development in mobile robot technology is the application of the principle of the inverted pendulum. This principle, with application to mobile robotics, means that a robot has two wheels and is able to balance itself by driving these wheels. A self-balancing, materials handling robot has been designed and built during this project. One of the most well known self-balancing robots that have been developed is the Segway Robotic Mobility Platform™, or RMP, which was designed for general mobility in robotics. The RMP has been distributed to research establishments, around the US, that are involved in robotics research as described in (Nguyen, *et al.*, 2003). These establishments have undertaken projects involving the RMP. Among these are projects in human-robot interaction as well as humanoid-robot mobility. There are also many people who have published work on self-balancing robots as hobby projects on the internet. However, these robots all serve the sole purpose of being able to balance themselves and nothing else. The main objective of this robot is the resolution of bottlenecks in reconfigurable manufacturing systems brought about by the changes in product flow within the manufacturing environment.

Reconfigurable Manufacturing Systems (RMS) have been in development since the late 1990's. These manufacturing systems are being developed in order to be able to adapt, as quickly as possible, to changes in products associated with changes in customer demands. Details on RMS can be found in (Mehrabi, *et al.*, 2000). The fact that the products, that the robot is going to transport are constantly going to change, means that the robot needs to be able to cater for products with different physical characteristics. The main characteristics involved are physical size and weight. As a first round approximation, the variation in loaded products, that the robot will carry have been limited by grouping products in families, in terms of a Part Family Architecture (PFA). PFA is the practice of grouping parts together in

terms of similarities like required manufacturing processes (Jiao and Tseng, 2000). In this case the characteristic that was used to group parts is geometry. Transportable products are also limited in terms of maximum dimension and maximum weight.

Stabilisers will be extended to the floor whenever parts or products are loaded or unloaded in order for the robot to align the Centre of Gravity (CoG) of the part with its own CoG. As soon as the CoG's are aligned the stabilisers are retracted and the robot will transport the part to its destination. The robot will be in constant contact with a client computer via wireless communication, and it will be able to navigate through its environment autonomously while avoiding collisions with obstacles in its way. This paper documents the design process that was undertaken in the development of the robot from conceptual phase through to testing and analysis.

2. System design

This section documents the process followed in the design of the complete system. A mechatronic engineering approach was adopted wherein each system is designed with the others in mind and when all are finalized, the systems are integrated and everything works together to fulfil the desired objective. The different systems considered are the mechanical system, the electronic system, and the software system. In this case the mechanical and electronic systems were designed to be integrated with each other while the software system is the tool used to integrate the two physical systems properly. The overall system can be visualised as shown in Fig. 1.

Fig. 1. Overall system diagram

2.1. Mechanical system

The two chief considerations, from the outset of this project were to design a mobile platform from the point of view of loadable parts, and the fact that it needs to be able to balance itself. These are two of the technical design specifications set in the early stages of the design process. The fact that the point of view of loadable parts was to be adopted, parameters were set on load characteristics. Loadable parts were roughly grouped in terms of geometry. These groups include prismatic geometries, pyramidal geometries, and profiles such as L-shapes, I-shapes and U-shapes, as well as flat plate. Loadable parts were also limited in maximum dimension and maximum weight, and this gives an idea of the types of materials that can be transported.

According to the load parameters as mentioned above, the technical specifications were set such that the load bed, and thus the robot is able to support and transport a load with maximum weight and maximum dimensions comfortably. Specifications were also set in terms of the dynamic operation of the platform in order to limit the maximum speed and acceleration to realistic values. In terms of interaction with the environment, specifications were set on the height of the load bed, in order for the platform to interface effectively with existing infrastructure. During this phase it was also specified that the platform should be statically stable when it is loading and unloading material and it should be dynamically stable when it is in the act of transporting materials.

The procedure of concept generation, consideration then selection was followed as soon as the technical specifications were finalised. Concepts were generated for the load bed actuation mechanism, the load bed support structure, the platform base structure, and the platform stabilisation mechanism. Load bed actuation was considered first keeping the loadable parts point of view in mind. A concept was chosen that allows the load bed to manipulate the loaded part in such a way that it is able to align the CoG of the part with that of the unloaded platform, in order for the platform to be able to balance with the extra weight. The load bed consists of two parallel rows of conical rollers. The two rows are individually actuated for relative motion. There is a single point dynamic load cell mounted on each corner of the load bed, these load cells will sense the position of the CoG of the loaded part and the part can be translated and rotated in order to align the part CoG with that of the unloaded platform. The two rows of conical rollers and the load cells can be seen at the top of.

Fig. 2. CAD model of physical platform structure.

In terms of the load bed support structure, the goal of this is purely to serve as an interface between the platform base structure and the load bed. A light-weight space frame design was chosen to serve this purpose. The platform base houses the wheels, stabilizers, and most of the electronics. A light-weight space frame design was also used for the platform base. Most of the parts are made of light-weight aluminium. Mild steel was used for the shafts and in areas where more strength and rigidity is needed.

2.2. Electronic system

The central component of the electronic system is the on-board computer. This is a single board computer with Epic form factor. The on-board computer will serve as a robot server and an external desktop computer will subscribe to the server in order to communicate with it. This will be discussed in more detail in the section on the software system. The on-board computer includes a SATA hard drive and SODIMM Random Access Memory. The on-board computer will communicate with the external client computer via Wi-Fi, using a USB Wi-Fi adapter.

The on-board computer is in communication with two motor controllers. One of these controls the drive motors via IFI Robotics Victor 885 DC motor drivers. The other controls the motors that will be actuating the load bed rollers, as well as the motors that will be actuating the platform stabilisers. In total six DC motors of

different power ratings will be mounted on the robot, i.e. two driving the platform, two driving the load bed rollers and two driving the platform stabilisers.

As mentioned before, single point dynamic load cells are being used on each corner of the load bed in order to determine the position of the part CoG. Readings from these load cells will be used to control the motors driving the load bed motors. Sensors that will be used to balance the platform include a MEMS rate gyroscope, a MEMS accelerometer, and quadrature wheel encoders. The data from all these sensors will be used to balance the robot effectively. For navigation, ultrasonic rangefinders and quadrature wheel encoders will be used for localisation and obstacle avoidance. The ultrasonic rangefinders have a range of up to six meters, and the quadrature wheel encoders have a resolution of up to 512 counts per revolution.

2.3. Software system

The software system of the robot revolves around the robot server installed on the on-board computer. This robot server is known as the Player robot server. The Player/Stage project is open source software developed by engineers and computer scientists around the world for use by engineers working in the field of robotics (The Player Project). This project also includes two dimensional and three dimensional simulation backends. The robot server allows an external PC to interface with, and control the robot, via a wireless network. In the case of this robot it is a Wi-Fi network. The Player robot server is able to send commands to motor controllers and also visualise sensor data such as ultrasonic rangefinder readings.

The motor controller controlling the drive motors houses a control system designed using control engineering principles, for balancing the robot effectively. This control system fuses data from the inertial measurement sensors and the quadrature encoders to keep the robot in an upright orientation. Gyroscopes provide instantaneous angular change but their data tends to drift over time, whereas accelerometers can give absolute angle of inclination, but they are sensitive to noise (Ooi, 2003). A gyroscope and an accelerometer are used together as their output characteristics can be used to complement each other. By fusing the raw data using the Kalman filter, one can produce much more accurate data. The Kalman filter is an algorithm that can be used to estimate state variables from noisy sensor measurements (Welch and Bishop, 2006). The Kalman filter and the control system can be embedded on the drive motor controller.

Another motor controller will control the load bed motors by using the measurements from the load cells, calculating what movements are needed to align the CoG of the loaded part with that of the robot. An algorithm will compare the readings from the load cells to determine which direction the part needs to move. It

will also calculate what the exact weight of the part is, and this will give an idea of how far the part needs to move in the determined direction. As soon as the part is in the correct position, a signal will be transmitted to the on-board computer signalling that it is ready to depart. This software will be embedded on the motor controller controlling the load bed motors.

The same motor controller that controls the load bed motors will be controlling the motors actuating the stabilisers. As soon as the ready-for-departure signal is given to the on-board computer, a signal is sent back to the motor controller informing it to retract the stabilisers. This back-and-forth signalling is a method of ensuring that the stabilisers do not retract before the control system is initialised and ready for operation.

In terms of navigation a number of ultrasonic rangefinders will form a sensor array around the robot; the reading from these sensors will be used by utilities incorporated in the Player project for localization in a mapped environment and also obstacle avoidance. There are multiple algorithms and strategies that have been developed for use with the player robot server, thus one can fit the most applicable algorithms to the specific situation. At this stage the most applicable navigational system for path planning using the sensors available and a map of the environment is Player's Wavefront propagation planner algorithm, based on the Adaptive Monte Carlo Localization algorithm for localisation, using the Vector Field Histogram algorithm for obstacle avoidance (The Player Project).

3. System Integration

System integration is one of the key concepts of the mechatronic engineering approach. In terms of mechatronics, system integration involves the integration of the systems mentioned in the previous section, i.e. the mechanical, electrical, and software systems, to produce an overall system that is able to solve a specific problem (Bolton, 2003). All the systems described in the previous section have been designed with eventual integration in mind.

The first level of integration is the physical level. This involves the physical integration of the mechanical system with the electrical system. The electronics need to be housed on-board the robot, in convenient, easy to reach areas for maintenance and operation reasons. Sensors like load cells form part of the physical structure of the robot. For this reason the structure needed to be designed around the mounting specifications of the load cells. Orientation of the inertial sensors has to be accurate in order for the readings to be accurate, thus machining of the mountings needs to be precise.

The next level of integration is the software level. In short the software system consists of the Player robot server, motor control systems, and the navigational

sensor control system. The control and information flow with the underlying electronic system can be seen in Fig. 3. The motor control systems need to know the characteristics of the robot in order for them to operate effectively. Thus, these control systems are designed specifically for this robot. The fact that the robot is going to be dynamically stable during operation means that the integration between the controller and the motors, and sensors, needs to be seamless for the robot to operate effectively. The Player server has a modular architecture which makes it simple to configure for specific hardware configurations (The Player Project). Many researchers around the world contribute to the hardware support database.

Fig. 3. Flow diagram of control and information.

4. Performance Testing and Analysis

This phase of the project involves investigating the individual dynamics of the robot, i.e. the controllability, and in the case of a self balancing robot, its dynamic stability. This phase also involves investigating the interaction of the robot with its intended environment of operation. The final step in this phase is the critical analysis of any results produced by testing.

Investigation of the individual dynamics of the robot involves firstly the controllability of the robot from a remote PC. It also involves, in the case of a self-balancing robot, the dynamic stability of the robot, in other words, the quality of the control system. This includes the reaction of the robot when loads with different weights are loaded onto the load bed. Simulations have been done in Matlab®, to determine the robustness of the control system that is being used for the dynamic stabilisation of the robot. A mathematical model of the robot was created and the reaction to a step input to the displacement of the robot was simulated for different robot weights.

The Linear Quadratic Regulator design technique (Bolton, 2003) was used to design a feedback control system that is robust enough to cope with variations in load weight. This control system was applied to the mathematical model of the system and simulated using Simulink®. Fig. 4 shows the response curves produced by these simulations. The simulations were run for the approximate weight of the unloaded robot, which is 50 kg, to the maximum load weight of 20 kg excess, which gives a total weight of 70 kg.

Fig. 4. Displacement due to a step input with different robot weights.

When inspecting the curves in figure 4 it can be seen that the variation in responses for the different robot weights is not significant. Although the average response time is relatively slow this is acceptable as the maximum speed of the robot will be limited in order to avoid parts sliding off the load bed due to acceleration and inertial effects. At closer inspection of the it is seen that that the rise times of the different responses only varies by approximately 0.7 sec. When evaluating the settling time of the responses it can be seen that this only varies by approximately 0.5 sec over the entire range of robot weights. The results of these simulations will be used to validate any results obtained from physical testing.

The working of the stabilisers are also examined, to ensure that the timing of extension and retraction is correct. In essence this step involves looking into the control and physical dynamics of all moving parts to ensure that everything works as it should. This includes, from the top, the rollers of the load bed, the stabilisers, and the wheels that drive the robot.

The interaction of the robot with its intended environment of operation is being examined. This is done to ensure that the robot interfaces with existing

infrastructure correctly. Another goal of this step is to investigate the operation of the robot in its environment, i.e. to determine whether the robot is capable of navigating through its environment, avoiding obstacles while transporting materials between manufacturing stations. The results of testing are being compared to the technical specifications and to simulation results, to identify and rectify any shortfalls.

5. Conclusion

A mobile robot has been designed for the purpose of resolving bottlenecks in reconfigurable manufacturing environments. The mechatronic engineering approach of system integration was used in order to produce a complete system that is able to solve the proposed problem. This system consists of a two-wheeled self-balancing robot, with a navigation system for path planning and obstacle avoidance and a communication system for communicating with other mobile robots in the environment and with a remote PC.

The design of the three elements that make up a mechatronic system were discussed as well as the integration of these elements. The integration of the three engineering disciplines was considered early on in the process to produce a more reliable and flexible system. The testing and analysis of the system was also discussed and motivated, including discussion of simulations and result validation. It is during the testing and analysis phase when it is determined whether the product of this project is feasible for use in an actual manufacturing environment. This project is an example of the applicability of mechatronic engineering in manufacturing technology.

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