Prototyping an Autonomous Guided Vehicle in Undergraduate Mechanical Design

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Abstract: Students majoring in mechanical engineering (ME) nowadays are required to study mechatronics at school as mechatronics plays an important role in modern product that often combines mechanical and electronic functions. However, most students have limited opportunities to be trained with hands-on experience in this field. This paper describes a team of ME juniors to accomplish an autonomous-guided vehicle (AGV) in a project-oriented mechanical design and practice course. An AGV is an automatically controlled vehicle that is often used in material transportation in an automated production line or in an automatic storage and retrieval system. It is a typical example of mechatronics as the vehicle is a mechanical device while controlled by electronics. A team of seven students is requested to complete the process of technical survey, design, analysis, parts machining, assembly as well as testing and refinement of an AGV in the two-semester course. The three-wheel AGV is driven by a DC motor, steered by a step motor, guided by two photo sensors, and position controlled by an array of three photo sensors with digital encoding. The AGV is controlled by a notebook computer with control algorithms designed and developed by students themselves. Students are not only highly appraised at the semester-end exhibition, but also fill with confidence in mechatronics after completing this course.

Keywords: AGV, mechatronics, mechanical design.

1. Introduction

Among many other industries, manufacturing industries, in particular electronics- and computer-related industries, are the fastest growing and most prosperous industries in Taiwan. One of the reasons is that engineering work and framework, but not creative idea, are encouraged and widely implemented. This also results in that OEM (original engineering manufacturing) has been one of the most important businesses in this country. While looking ahead, industrial and governmental leaders foresee that manufacturing and fabrication industries, though they are the most profitable industries at this point, will not last too long as near-by countries are also promoting similar strategies and industries with somewhat better benefits for investors. As one of these leaders' conclusion, product design will be one of the key industries and needs to be stressed on in order to transfer from current status to a more competitive situation in the next decade.

Product design, however, needs both vertical integration of different phases of product lifecycle and horizontal integration among related technologies and industries. Industries, though handy in manufacturing and fabrication, are often lacking of creative idea and basic supporting theoretical background. This is one of the critical issues for the transfer from current fabrication-oriented industries to design-oriented industries.

As technologies for product design and manufacturing change and improve relatively fast, product life cycle is thus dramatically reduced. While college graduates are the most important source of higher-level manpower for industry in Taiwan, engineering college students are expected to be sharpened with product design and manufacturing knowledge at school, in addition to theoretical analysis capability. This is an important issue in particular when industry faces the increasing competition in the global marketplace nowadays. It is obvious that college curriculum and courses must be designed to meet this challenge in order to lead students to become productive engineers in their future[1,2].

A mechanical engineer, however, should equip himself/herself with the knowledge on how to translate engineering problems and demands into design analysis, and prototyping. Students at school are supposed to learn the process and methodology related to integrating and to testifying the entire process. This is part of the training to let students understand how to apply the knowledge and techniques learned in class to practical problems. A curriculum based on this concept has been implemented in the Department of Mechanical Engineering of the National Chung-Hsing University such that a series of "Mechanical Design and Prototyping Projects" (MDPP) were organized to offer students to explode project-oriented practical problems. These courses emphasize on hands-on practical training of mechanical design and prototyping processes in addition to theoretical analysis training [3]. These hands-on training processes are expected to stimulate students' creativity and cumulate related knowledge in the learned process. It is also one of the goals of the MDPP courses that experience interchange through industry-supported projects will provide students with more practical experience besides theoretical training in the college. Students are also expected to learn the methodology and attitude of teamwork through these processes.

From another aspect, conventional manufacturing industries in Taiwan are still labor-intensive though their manufacturing and fabrication technologies have been worldwide famous. The government has noticed in the early 1980s that automation technology will play an important role in improving this nation's industrial competence. A nine-year three-phase nation-wide program on developing automation technologies has been formed since then to improve the productivity of industry by transferring labor-intensive industries into technology-intensive and capital-intensive industries. Under this program, educational institutes have stressed on training students with automation-related knowledge and technologies. Several curriculums on automation technologies, such as mechatronics, information technology, computer-aided engineering, manufacturing process automation and office automation, have been formed and taught at engineering colleges in the past decade. Among these technologies, mechatronics is one of the most difficult technologies as it combines mechanical, electronic, and information technologies. It is a key technology in modern product design as a product often combines both mechanical and electronic functions to make itself intelligent and smart. However, students majoring in electric or electronic engineering often pay less attention on mechatronics partially because that they usually have difficulty to get into the depth of mechanical-related knowledge and technologies. On the contrary, students majoring in mechanical engineering often treat mechatronics as an advanced course as it involves electronics, sensoring and signal processing, as well as control and software or firmware engineering. As a result, very few undergraduates are trained with mechatronics in class that in turn makes them even difficult to try mechatronics-related jobs in their career. [5]

This paper describes a mechatronics project completed by undergraduate juniors major in mechanical engineering. It is one of the projects developed in the class "Design and Prototyping of Automated systems" (DPAS) in the MDPP program. Students combined their knowledge in mechanical design, analysis, machine shop, electronics, sensoring and control, information technology, and, the most important, their creativities to complete a prototype of an autonomous guided vehicle (AGV), an unmanned vehicle commonly used in manufacturing and office automation. We start with the introduction of the MDPP program and its philosophy. Course design of the DPAS is then introduced as the project-oriented class is conducted in a different way from regular class. Implementation and progress of the AGV project is then reported. The paper then gets into more detail of the design and prototyping process of the AGV followed by the conclusion and discussions.

The MDPP curriculum was organized in such a way that project-oriented classes are offered to juniors and seniors as they have completed basic required courses and certain advanced design and supporting courses. The curriculum is designed in such a way that students learned the process and related methodologies in mechanical design with hands-on experience and have a better idea how to apply what learned at school to engineering problems [4]. The MDPP series of projects were first offered at the department in the 1995 academic year. The DPAS class, an extension of a previous design and manufacturing project supported by the Ministry of Education (MOE), has been designed as one of the series of MDPP since then.

However, as students have limited hands-on experience on implementing their design that often needs to be modified again and again until it becomes practical. The MDPP course provides a one-year long step-by-step process. To have students learn related knowledge and technologies efficiently, approaches employed in this series of courses includes learning by doing, teamworking, and brainstorming [5]. It has been reported that this approach is quite successful for training undergraduates with hand-on experience. The series of courses are also highly praised by students as they do learn how to apply knowledge in class to prototyping a device and/or methods for stimulating creativity and teamworking together.

2. Course design

The DPAS is one of the MDPP courses to offer students projects on design and prototyping mechanical systems or sub-systems based on automation technologies. Typical knowledge and technologies include computer-aided design, mechanism design, sensoring and control, system integration, and information technologies. Students in the class are required not only to develop the mechanical and electronic sub-systems, but also to use their creativity to think about possible applications of the developed systems. Students are teamed up and required to design and to prototype automatic systems based on their own designs, but not just paper work. They are required to define their target and then taught how to search related information and to do analysis in order to complete design and to implement their goal. Each student from each team is required to deliver a weekly progress report and/or demonstration of their project. This has shown a great success in tracking each project.

This DPAS course was designed to give students extensive knowledge and practical experience on mechanism, structure, dynamic system, sensing, control, and mechatronics. Projects completed in this class include prototypes of a computer controlled Automatic Storage/Retrieval System (AS/RS), a rotary type storage system, an electric elevator, an anonymous guided vehicle (AGV), and an electricity-powered motor vehicle. In this paper, we will discuss the AGV project as an example.

As students have some kind of fear of mechatronics because electronics is not taught until junior class. Nor the sensoring and control courses are taught after the electronics course. It is difficult to enforce students to study mechatronics in this situation. This condition, however, can be improved if students want to implement mechatronics on their project. Students have much stronger motivation to learn related knowledge as they have to design and implement such an automated system. It is not too difficult for instructors to lead students with such motivation that we give students suggestions that can make their system smarter and more intelligent. Students often appreciate such suggestions and comments as this makes their design better. In order to achieve better function, students then force themselves to implement mechatronics in their original design. The design then becomes students' "dream" that they want to have it come true.

In addition to regular mechanical design and analysis, additional material are taught in the DPAS class as projects in the class are intended for students to apply mechatronics technologies. Because mechatronics involves hardware and software engineering, knowledge in the following fields are enhanced in the class [5].

1. Sensing and sensor technology, including positioning and motion sensoring as they are important for mechanical behavior and motions.
2. Micro-computer-based digital control, in particular motion control of mechanical systems.
3. Signal processing technology, especially signal conversions between digital and analog signals and signal conditioning techniques.
4. High-level programming languages for microcomputer I/O (input and output) control such as C and C++.
5. Low-level programming languages for programmable logic controller (PLC)

In the class, we encourage students to use micro-computer together with plug-in I/O cards to develop control schemes as these are commonly available, easy to program, and relatively economic. As for sensoring, we encourage students to use commonly available sensors, such as limit switches for positioning sensing and optical sensors for motion tracking. Combining these sensors, students also learned how to do simple pattern recognition based on simple encoding and decoding techniques. In the following section, we use the AGV as an example to describe the design and prototyping process developed in the DAPS class.

3. Design and Prototyping an AGV

AGV is one of the most commonly used transportation vehicles in automatic systems. The vehicle, together with AS/RS or production line, is used to carry material, parts, subassemblies, and products from one workstation to another one. It differs from common vehicles in the guidance system as it is autonomously guided though the sensoring and control system. An AGV consists of hardware and software. The former includes the mechanical structure of the vehicle and the power transmission system as well as electronic hardware for sensoring and control. These two parts are integrated by the control system driven by control schemes, coded in software.

The design process includes the following steps: survey and define functional specifications, conceptual and functional design, detailed engineering design, manufacturing planning, material preparation, parts machining and components purchase, system assembly, sensing and control assembly, system integration, adjustment and refinement. We briefly discuss some of these steps in the following subsections.

3.1 Survey and define specifications

In the beginning, students have no idea what an AGV is though some of them saw the picture of AGVs in previous classes. As the first step in product design is to form the problem, we started this project by some introduction material including the function and applications of AGVs in automated systems. Some functional specifications, hardware and key characteristics are also hinted and suggested. While we keep the approach "learning by doing" in mind, several literatures, references, magazines, and videos are suggested or requested for students to read or watch as a survey. Although this is the first project these students ever experienced, they showed no fear to face the challenge. Some key characteristics students are asked to survey including the following items:

- Structure and power system: Structure of an AGV often based on its loading, motion characteristics such as speed, as well as working environment. The structure can be very different for and AGV used in FMS (flexible manufacturing system) and in an office as the former must be stiff with high power in order to carry parts used in a production line while the latter is often light with silent power system as it is often used to transfer documents or stationeries among offices.
- Path planning and guidance system: This characteristic depends on the function of the AGV. While an AGV employed in a factory needs simple path and robust guidance, an AGV used in office may be required to equip with good path planning and guidance system as its path is often complicated. Several sensing and guidance methods were surveyed in order to understand the state of the art of sensoring and positioning technologies.
- Sensing and control: This is often the weakest part for ME-majored students as they have limited knowledge on electronics and sensoring technologies at the time when they took this class. This item is close related to the guidance system as the accuracy of movement and positioning are determined mainly by the resolution and sensitivity or sensors and controller. Several different sensoring technologies and corresponding control schemes are reviewed for designing the AGV.

In addition, there are several related technologies involved in the design and fabrication of an AGV because it is an integrated system. Table 1 shows the state of the art of technologies involved in the AGV system and possible choices.

Table 1. Survey of technologies involved in the AGV system and possible options

Technology	Options
Driving system Motion control	Three- or multi-wheel, Constant-speed, constant torque, constant power
Positioning method Guidance method	Mechanism-based or sensor-based Optical, metal band, electro-magnetic, laser-sensing, wireless
Control system Communication method	Centered, distributed, hybrid, PC-based Wired, wireless, networked, stand-alone
Power supply Safety mechanism	DC with automatic, spare, or fixed charge Sensor-based, (contact and non-contact) with bumper
Control scheme	Analog or digital

Because the goal of this project is to design and prototyping an AGV from scratch the team, together with project advisors, decided the following specifications:

- Primary function: An AGV used in an office environment for documents and stationary transferring. To simply the path planning and positioning technologies, the AGV will be designed to move in straight path.
- The mechanical structure: two-floor simple and light structure such that material can be put in either floor. The driving system should be a three- or multi-wheel structure for stable motion.

- The driving system: DC-powered motor driving system so that the AGV can move as far as possible but not limited by the power line.
- Sensing and control system: Optical sensors are used for positioning and path tracking as this non-contact technology can be employed in an office environment. Only position control is considered for this first-generation AGV.
- Control system: PC-based control with wired connection. A notebook with parallel I/O digital control is allocated for this purpose.

A draft design, based on the above specifications, with the rear wheel, driven by a DC motor, as the driving wheel and direction controlled by the front wheel steered by a stepping motor is shown in figure 1. Two auxiliary wheels are designed to keep the system is stable position. The structure is composed of steel frames and two steering sensors, not shown in this figure, are located in the front of the frame.

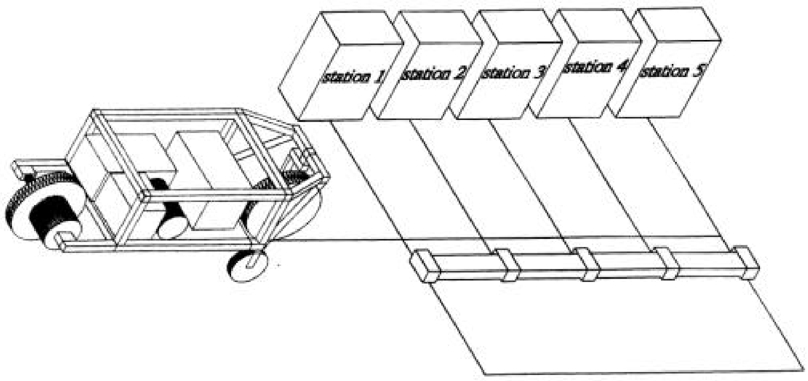

Fig. 1. Sketch of a five-station AGV system

3.2 Concept and detailed designs

Based on the functional specifications, different possible structures and mechanisms that satisfy functional requirements are brought to class for discussions. The structure of the AGV was first sketched and brought to discuss in the class. It was then revised based on comments and suggestions from project advisors and other classmates. This is intended to let students understand the design loop from functional specification to concept sketch, to functional check, to design for manufacturability and assembly (DFMA) check, and design revision. The structure of the first draft is not determined until functional specifications and some DFMA evaluations are checked. This stage, from our experience, usually requires four to six weeks as students' concept is solidified during this stage.

Detailed design analyses are then conducted that includes structure strength analysis, friction and transmission system analysis, efficiency and power analysis, DFMA analysis, resource planning, time and cost estimation. This is the standard training for engineering students so students feel comfortable and learned how to apply knowledge learned in class to this project. Engineering drawings, including parts, sub-assemblies and assemblies, are then prepared using CAD system as design changes are expected in the following phases.

Direction guidance is controlled by two photo-based steering sensors that detect signals from a metal band in the ground. Control scheme are developed to determine the direction of rotation of the front wheel based on simple algorithms. Signals from steering sensors are sent to a notebook PC via an 8255 card with analog I/O. Position is detected based on contact sensors allocated at each station. Digital encoding schema is developed to detect up to eight stations based on three sensors. The positioning signals are also transferred to the control computer through the 8255 I/O card. Signals are sent to activate the on/off switch of the DC motor that drives the driving wheel. Electronic circuits are designed and to meet the interface and I/O specifications.

The detail design phase is a time-consuming process. As design is a trade-off among different aspects thus design change is common after design analyses and evaluations. It is common that students spend two months in the detail design and analysis process as they are often not familiar with the problems they faced, nor are they handy to apply knowledge in the engineering problem.

3.3 Parts preparation and assembly

Detailed engineering drawings of machined parts and components from the above design are then prepared. As each project has limited budget most parts are machined by students themselves, unless the precision are too high to reach for machine tools in the workshop. Students are requested to prepare material in this case. Some commercially available components are directly purchased, often from used parts market to save money. This is another training for students to understand how to achieve their goal under limited resources.

The AGV system is then assembled at the same time when parts and components are prepared. This is also part of the training for students to get some feelings on the "concurrent engineering" technique. Figure 1 is a snapshot in the assembly process that a student was locating and connecting the battery cell to the DC motor, shown in the center, which drives the rear wheel via a roller chain.

3.4 Assembly of sensing and control systems and system integration

The sensing and control systems are designed and assembled at after the design and assembly of the mechanical structure. In this AGV, there are two subsystems for sensing and control: the guidance system and the positioning system.

As mentioned that the AGV is guided by a metal band with photo sensors to detect the path. Two photo sensors, located in the front of the AGV frame, are arranged in a distance slightly smaller than the width of the metal band. Offset of the AGV, when it moves, can be easily detected as soon as either sensor sends no signal. Direction correction is made by controlling the stepping motor which turns the front wheel to correct the offset. Positioning for the five-station is made possible by three limit switches as they can be encoded in 8 different combinations. The three limit switches are positioned on the AGV while each station is equipped with a unique configuration so that position can be easily detected when the AGV moves.

3.5 System testing and refinement

The assembled system must be testified against the specifications. This is often in the final stage close to the end of the one-year project-oriented class and thus a little bit tight in schedule. However, this process is always required though students are sometimes kind of frustrated after the whole-year long project. Therefore a semester-end exhibition is designed in the MDPP classes that all projects must show their work at the end of the class. Students are forced to do the test and adjustment otherwise they are unable to demo their year-long achievement.

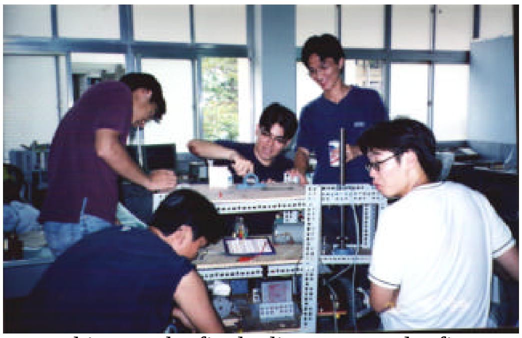

Fig. 2. Students working on the final adjustment and refinement in the final stage

Figure 2 shows that students are making final adjustment after testing. We find in the DPAS class that students usually did more work efficiently during the week before end-semester. It is very common that students modified their designs in the final stage. This is partially because that they are now very familiar with their project and feel comfortable to make a quick change. This is part of the goals of the MDPP classes as students are more confident after completing their project by the end of academic year.

4. Conclusion and discussions

This paper discussed the philosophy, design, and implementation of the project-oriented DPAS class, as part of the MDPP classes, with an AGV example. Important steps involving the design and prototyping of the AGV are also briefly discussed in the paper. The project-oriented DPAS class is designed to give students more hands-on experience in mechanical design and prototyping and system integration via mechatronics. It also gives students more exploration to related knowledge in addition to theoretical training. This class has been proven a great success that students are trained not only to complete semi-industrial projects with their own design but also to learn the methods and skill for teamwork and brainstorming. It also proven that such arrangement can stimulate students' creativity as one of the projects has been granted the ROC patent and some others are patent pending. [Tsai et al. 1999] As engineering education plays an important role in the society, curriculum and courses must be carefully designed to ensure that students are learning what required in the society.

Although we discussed in previous section some steps involved in the design and prototyping an AGV, many considerations are put into the training including resource management, project management, as well as teamwork. Students are asked to plan working items and schedule when the first draft design is completed. This is to remind them how many work in the following process and how much resource, including budget, manpower, and time they have. As these items often become critical issues when they face industrial projects. We noticed that students did appreciate this kind of training from queries. We would like to share our experience in this paper as many institute and universities in Taiwan now noticed that students need hands-on experience in undergraduate.

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