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PROTOTYPING A REMOTELY-CONTROLLED MACHINE FOR CONCRETE SURFACE GRINDING OPERATIONS

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Abstract. The surface of concrete pavement needs to be flattened for the smoothness and comfortability of highways. Surface grinding can provide flatness in the hardened concrete surface, and improve adhesion between the existing concrete surface and the subsequent layer. The surface grinding process, however, is executed under hazardous work conditions and the outcome is affected by a machine operator's skill. Automation of this process can provide a hazard-free work environment and increase the quality of the ground surface. This paper presents an application of an automated concrete surface grinding machine that an operator can remotely control with computer assistance. A combination of hardware and software technologies was applied to prototype automated functions of the machine. Field tests demonstrated that remote control of concrete surface grinding is feasible and can be utilized as a semi-automated scheme on actual construction sites.

Keywords: automation, concrete surface grinding, remote control, dust collection, machine tracking.

Introduction

Concrete surface grinding is frequently applied in concrete work for infrastructure such as pavements, bridges, airports, and buildings. The operation provides flatness in the hardened concrete surface and adhesion between concrete layers during new construction and maintenance operations of existing concrete surfaces. For concrete pavement, surface grinding is necessary to remedy the defective sections of the concrete or to remove irregularities in adjacent joint sections. The process is also done to smooth out the distressed layer of pavement surfaces. Concrete surface treatment can enhance surface resistance and structure stability.

Currently, concrete surface grinding is primarily done manually and largely depends on an operator's skill. During the operation, workers are exposed to dangerous noise and dust conditions. Additionally, if not taken into careful consideration, the dust residue can be an environmental hazard to the surrounding area. As the operation is labor-intensive, this hazardous working environment can also result in poor work performance. The market demand for concrete surface grinding work is ever growing due to new construction and is also necessary for the maintenance of various facilities, including highway pavement (FHWA 2006). With this in mind, additional attention and solutions are necessary to improve work conditions and concrete surface grinding quality.

Automation is one method that may replace or assist workers and improve quality of concrete construction (Kunigahalli, Skibniewski 2008). Concrete surface grinding can also benefit from the automation technology. It may improve productivity and quality of grinding operation. This would prevent safety accidents, caused by a lack of experience or mistakes, and minimize air and water pollution. There are several challenges in implementing automation for concrete surface grinding as the grinding operation is exposed to weather conditions and requires high-powered equipment that would be operated in an unstructured work environment. Therefore, the extent of automation possible needs to be carefully considered in implementing automation for concrete surface grinding.

The degree of automation may vary from simple mechanization to fully-autonomous robotization. In many construction and/or maintenance applications, semi-automation or computer-assisted tele-operation schemes were found to be more successful over full automation (Skibniewski, Hendrickson 1990; Skibniewski *et al.* 1993; Kunigahalli *et al.* 1994; Haas *et al.* 1997; Cousineau, Miura 1998; Seo *et al.* 2000, 2007; Bernold 2007; Sasaki, Kawashima 2008; Yamada *et al.* 2008; Kim *et al.* 2009; Tang, Yamada 2011; van Osch *et al.* 2014). Semi-automation also fits well with characteristics of the concrete grinding operation and with a certain degree of as-

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sistance from a computerized controller. Therefore, this study develops and evaluates a prototype of a remotely-controlled concrete surface grinding machine capable of improving the current practice in concrete surface grinding. The knowledge and experience from the lessons learned during the prototyping would be valuable in designing a remotely-controlled concrete surface grinding machine and other types of machines for automation in the construction industry.

This research was conducted in the following steps. First, the problems associated with the operation of existing concrete surface grinding were identified to justify the need for the development of an automated machine. Second, the hardware components of the machine, including the mechanisms for driving and grinding were designed and developed. Third, a remote-control system was developed that includes path-planning software, a wireless remote controller, and a MMI (Man-Machine-Interface) system. A quality inspection module was also provided to remotely monitor the ground surface quality in real time. Finally, the validity and effectiveness of the developed prototype was tested through field tests.

1. Analysis of current practice and automation efforts

The concrete grinding machinery being used today is primarily based on manual operation that relies on an operator's skill. In this section, existing surface grinding machines and operation are analysed to identify the requirements in designing an automated surface grinding machine. The efforts that have been made to automate concrete surface work including grinding, cleaning, and finishing operations are also analysed to identify and study the component and/or functions of the grinding machine that could be automated.

1.1. Existing concrete surface grinding machines

Figure 1 shows a typical concrete surface grinding machine that is frequently used for smoothing roadway pavement. The grinding machine shown in the figure has a grinder of 80 cm in width, and 300 kg in weight. The size and weight of the grinding machines vary depending on the width of the grinder part. The grinder is made of diamond blades, and powered by a diesel engine. While the surface grinding is in operation, the main power to drive the machine forward is generated by the friction between the diamond blades and the concrete surface. In other words, the grinder simultaneously functions as a surface grinding device and as a driving mechanism.

When the equipment is not in the grinding mode, the operator needs to move the machine around manually by manipulating the driving wheel with his hands as shown in Figure 1. The steering is also done manually by pushing the machine in the desired direction. When the equipment is in the grinding mode, the operator needs to hold the machine's handle stick, control the torque of the engine, and adjust the height of the blades from the concrete surface as shown in Figure 1. If necessary, the operator pulls the machine using a handle stick to avoid unwanted forward movement of the machine. Therefore, the operator needs to be skilled in order to achieve the expected level of productivity and quality. The manual operation is also very physically demanding.

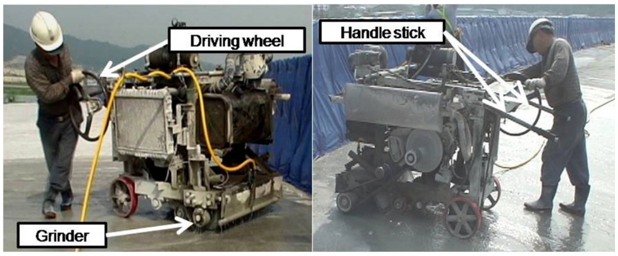


Fig. 1. Existing manually-operated concrete surface grinding machine

1.2. Steps in manual operation

The current operation of the concrete surface grinding process consists largely of three stages: 1) planning, 2) implementation, and 3) evaluation. In the planning stage, the information on the status of the concrete surface is obtained by using equipment such as a profilemeter in order to select the area to grind and to create a work plan. The implementation stage is to set the machine on site, and execute the operation of concrete surface grinding. Dust created during the grinding needs to be collected and disposed, as it is a threat to the health of the worker and a cause of air pollution. Dry grinding needs some type of vacuum device to collect the created dust. Wet grinding includes water spray by which dust and water are mixed together into a sludge, which must also be properly removed. Finally, the evaluation stage includes inspection of the ground surface quality. During this stage, once the surface grinding is completed, the operator checks the quality to determine whether it meets requirements and makes a decision on whether or not to do rework.

1.3. Efforts for automation of concrete surface work

Concrete surface work typically includes grinding/grooving, cleaning, and finishing. Although this paper focuses on the concrete grinding work, the efforts that have been made to automate these three types of surface work are analysed in this section because they have similar operational characteristics.

A Japanese contractor developed a prototype robot called MTV-1 (Multipurpose Traveling Vehicle) for grinding and cleaning of concrete slab for buildings. This prototype has a traveling module (vehicle), and either a cleaning module or a grinding module can be attached to the vehicle. It was designed specifically for building slabs, and it travels based on a traveling algorithm and avoid obstacles such as columns based on ultrasonic and gyro sensors (Kangari, Yoshida 1989).

Another Japanese contractor developed a series of concrete floor finishing robots. Trowel-finishing operation for building slabs was automated. The first generation of this robot was too heavy weighing 700 kg with too many components. It has self-navigation capability, but it was reported that the programming was difficult and time consuming. The second generation of this robot reduced the number of its components, and the productivity was raised because of the lighter weight and the simpler programming scheme compared to the first generation. The final and more simplified version of the robot gave up self-navigation and/or pre-programming. Instead, it adopted manual remote-control scheme. With the lighter weight and the eliminated programming time, the productivity went up by more than 100% compared to that of the first generation robot (Cousineau, Miura 1998). Other attempts are also found in the area of the control schemes of surface work automation. Zhou and Skibniewski (1994) studied the force control of the construction manipulator that has to maintain contract with the surface. Shin and Han (2003) recently suggested an open-loop velocity control of concrete floor finishing robot. Based on the observation of the robots developed 80's–90's and the one developed most recently, it was concluded that remote-operated or semi-automated system have better productivity compared to self-navigation or pre-programming for concrete surface work because of the unstructured and force-requiring nature of the concrete construction work.

Partly or semi-automated grinding machines compared to the manually driven grinding machines have also been developed for bridge deck and dam construction. A grinding/grooving machine for bridge concrete decks was developed and is being utilized currently (DOT Diamond Core Drilling Inc. 2014). It has a four-wheeled vehicle as a driving mechanism and a grinding unit that can move around and operate within the rectangular space provided in between the four wheels. The operator still has to ride the vehicle to drive the vehicle and operate the grinding or grooving unit with a joystick, which becomes the hazard to the operator because the operator is exposed to the dust created during the operation. Other grinding/grooving machines of this nature are also found (A-core Inc. 2014). The quality check to provide the required evenness and grinding depth of concrete surface is also a very important function of a grinding machine. Therefore, a surface profiler is required for the quality assurance of grinding operation. A surface profiler that is attached to a different vehicle than the driving mechanism of the grinding machine itself is typically utilized in the market (Surface Systems and Instruments Inc. 2014).

Grinding machines were utilized for dam construction as well. A dam spillway failed to meet slab smoothness specification after construction, and a grinding machine with a diamond blade was used to grind down the uneven surface of the spillway. Because of the steep slope of the spillway, the winches at the top of the dam were used to control the machine. A robot was also developed to repair the eroded concrete surface of the spillway of a dam. The robot used high pressure water jetting to selectively remove only the weakened and damaged sections of the concrete spillway. The water-jetting end effector was operated from a platform designed for the geometry and slope of the spillway channels. The platform was controlled by four winches mounted on the crest of the dam (PDworld 2014).

2. Performance criteria for automation of concrete surface grinding operation

Performance criteria for concrete surface grinding need to be established to meet functional requirements for automation. Through the interview and workshop with operators and an equipment developer, several performance criteria for concrete surface grinding operation were determined in terms of safety, productivity, and quality. The selected performance criteria were further broken down into specific metrics that represent detailed requirements for consideration in automation of concrete surface grinding. The performance criteria summarized in Table 1 were used in designing a remotely-controlled machine prototype for concrete surface grinding.

Table 1. Performance criteria for concrete surface grinding

	Performance criteria	Concerns
Safety	Labor's health	Dust, Noise
	Physical hazards	Overexertion, Collision
	Environmental pollution	Amount of dust of sludge
Quality	Maneuvering accuracy	Planned path vs. actual path
	Grinding depth	Variance of grinding depth
	Quality measurement capacity	Errors in checking work performance
Productivity	Maneuvering speed	Moving speed for re-positioning
	Grinding speed	Grinding speed
	Path-planning capability	Efficiency of work path

First, to monitor safety in the concrete surface grinding operation, three performance criteria were considered. Workers are exposed to the concrete dust created during the operation, especially with dry grinding and this is a concern for respiratory health. The operation is also physically demanding and can result in accidents, thus requiring a decrease in the level of physical hazards. The dust, whether in wet or dry conditions, also causes environmental pollution that should be avoided.

Second, in regards to ground surface quality, maneuvering accuracy was considered as a performance criterion. A certain level of maneuvering accuracy is required to avoid problems caused by missing or overlapping grinding areas. Another criterion related to the ground surface quality is grinding depth. The grinding depth should be consistently maintained throughout the operation to avoid re-work. Any over-grinding may involve damage to concrete strength. Thus, the prototype should be able to provide the operator with the ability to measure the work performance and to inspect quality in an automated manner.

Third, for grinding operation productivity, the speeds of the machine during the grinding mode as well as the maneuvering (no grinding) mode were selected as performance criteria. Even if a machine has adequate maneuvering and grinding speed, the operation cannot be performed efficiently if the path of the operation is inadequately planned. A path-planning capability was therefore selected as a performance criteria related to the productivity of the operation.

The ideas and technologies to automate and/or improve the current operation were reviewed to achieve better performance with respect to the identified criteria. Since the grinding work requires highly accurate control and measurement, it was determined that computer-assisted remote control, rather than full automation, would best satisfy the performance criteria given the dynamics of the grinding operation. The selected criteria were also used for the qualitative comparison between the prototype and existing machines. The performance of the remote-controlled prototype was compared to that of current manual operation as an indication of automation effectiveness.

3. Design and fabrication of a hardware system

Remotely-controlled surface grinding requires the combination of hardware and software technology. The hardware provides a capability for actuation that is required to perform the grinding operation. Using actuators such as hydraulic cylinders and electric motors powered by diesel engine, the hardware system components should work to execute the commands from a human operator or an autonomous controller assisted by sensing and software technologies. This section explains these hardware components of the prototyped remotely-controlled concrete surface grinding machine.

3.1. Overview of the system structure

The system structure was designed to effectively actuate the prototype for concrete surface grinding with a power source and actuators as shown in Figure 2. The hardware part of the prototype is made up of a main power source using a diesel engine and three core mechanisms for: 1) driving, 2) grinding, and 3) dust collection. Two DC motors were used for the driving mechanism for more precise control than would be expected from a diesel engine and the directional control is accomplished via a steering mechanism powered by a hydraulic cylinder. The grinding mechanism includes a grinder with diamond blades. It rotates via a power belt that is directly connected to the diesel engine. Another hydraulic cylinder is used to actuate the lifting and lowering of the grinder. The dust collector, which is basically a vacuum device with a vacuum pump and a hopper, also operates via the diesel engine directly through a chain. The body of the concrete surface grinding machine that contains the hardware system components is 110 cm in width, 210 cm in length, 115 cm in height, and about 1 ton in weight.

3.2. Hardware components

Figure 3 depicts the four major hardware system components of the final prototype for the remotely-controlled concrete surface grinding machine, these include: a) a power source, b) driving mechanism, c) grinding mechanism, and d) dust collecting mechanism. A detailed description of the hardware system components of the prototype along with the design rationales is included in this section. In the course of prototyping, efforts were made to improve the performance of the prototype. Lessons learned from the prototyping to improve the design are also explained here.

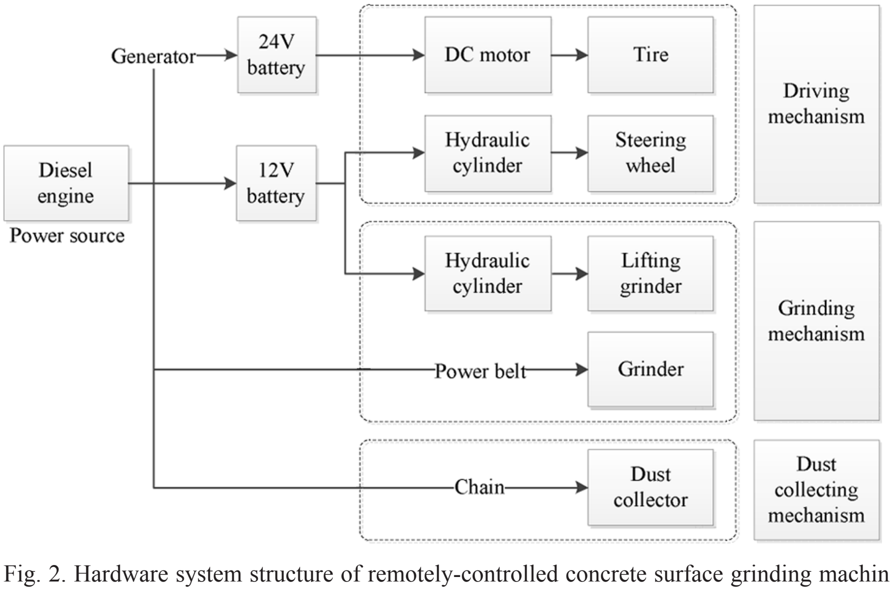
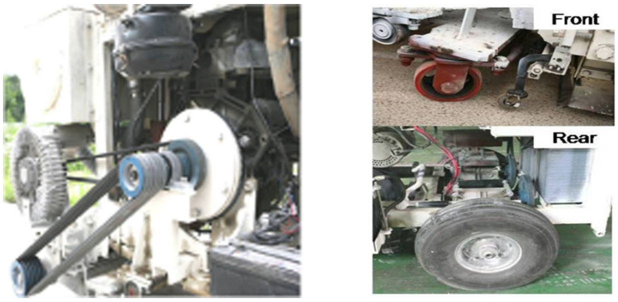


Fig. 2. Hardware system structure of remotely-controlled concrete surface grinding machine



(a) Power source

(b) Driving mechanism

(c) Grinding mechanism

(d) Dust collecting mechanism

Fig. 3. Prototype hardware system components

3.2.1. Power source

A 2400 cc diesel engine with 140 hp was selected as the main power source of the prototype. The engine rotates the diamond grinding blade through the power belt as shown in Figure 3(a). A diesel engine was selected over a gasoline engine because of the rotational velocity and the torque required grinding a concrete surface with a series of diamond cutter heads. Other power sources were also necessary to drive the machine. A 24 V battery and a 12 V battery were power sources for the DC motors and the hydraulic cylinder, respectively, and for the driving mechanism. The 12 V battery is also the power source of the hydraulic cylinder that lifts and lowers the grinder. The diesel engine also provides power to the generator to charge the batteries of the DC motors of the driving mechanism while the blade is not in operation. The vacuum pump of the dust collector is also operated directly by the diesel engine.

3.2.2. Driving mechanism

The driving mechanism is composed of two rear wheels for driving, and two front wheels for steering (Fig. 3(b)). Two DC motors were used to drive the rear wheels. These electronic motors allowed precise manipulation of the machine during the operation using the remote controller. The operator can control the velocity of the DC motors by varying the amount of voltage, and move the machine forward and backward. The DC motors are operated by a 24 V battery, which is charged when the generator is operated. The generator is directly connected to the diesel engine with an on/off switch. The steering wheels are located in the front, and it is operated via a hydraulic cylinder powered by a 12 V battery.

The driving mechanism is used when the grinding is not in operation. That is, the operator can use the DC motors to position the concrete surface grinding machine at any desired location before actual grinding work starts. Therefore, the driving force of the worm gear in the DC motor was sufficient for driving.

In the initial stage of prototyping, the machine was steered by differentiating the rotational speeds of the two rear wheels. Although this initial version of the steering mechanism was simpler in that it did not add another actuator for steering, it was difficult to achieve satisfactory accuracy and responsiveness. Therefore, a set of front wheels with a separate steering actuator was added to increase the maneuverability by improving directional control. Such an addition helps the machine rotate up to 45° to the left and right at the minimum rotation radius of 180 cm.

Other lessons learned on the design of the driving mechanism through the tests in the course of prototyping are as follows. In the first attempt, two rubber tires without air pressure, but with a series of teeth to prevent tire slippage were used for the rear wheels. The teeth of the tires, however, were broken after several performance tests as shown in Figure 4. Tire slippage also made the steering operation via differentiation of the rotational speed of the rear wheels very difficult. As a counter measure, rubber tires with air pressure instead of rubber tire without air pressure was applied to improve the durability and stability of the rear wheels as show in Figure 4. Additionally, in the initial design of the prototype, AC motors were adopted to control the machine, and the electric power was supplied to the motors directly from the generator of the diesel engine. These motors, however, did not provide sufficient power to drive the machine when the engine load went over a certain limit. Therefore, DC motors were applied for the final version of the prototype, and a 24 V battery was employed to provide the electricity to the DC motors.

Fig. 4. Prototype tire improvements

3.2.3. Grinding mechanism

Two grinding methods were considered for the prototyping: dry grinding and wet grinding. In this study, dry grinding was applied to the machine to avoid the sludge that is created by wet grinding and which is harmful to the environment. The dry grinding takes advantage of the grinder with a series of diamond cutter heads at 100 mm in diameter (Fig. 3(c)). The prototype is designed to execute grinding work by bringing the grinder into contact with the concrete surface. Therefore, a diesel engine with a high maximum torque was selected to secure satisfactory rotational speed and torque force. A 2400 cc diesel engine with 140 hp was considered to generate enough power for the operation of concrete surface grinding. The height of the grinder blade was controlled using a hydraulic cylinder to adjust the depth of surface grinding. There are also two wheels that limit the grinding depth of the diamond blades and prevent any excessive cutting into the concrete as shown in Figure 3(c).

3.2.4. Dust collection mechanism

Dust created by the dry grinding should be controlled to protect the work site and the surrounding areas from air and environmental pollution. Unless thoroughly removed, the dust residue would also cover the ground surface making quality-control inspection difficult. Therefore, a dust collection mechanism was devised. It is composed of: 1) a vacuum pump to suck up the concrete dust, 2) a hopper to store the dust, and 3) cartridges and filters inside the hopper (Fig. 3(d)). The vacuum pump was powered by the diesel engine of the surface grinding machine.

Unfortunately, the performance tests showed that the vacuum pump was not powerful enough to completely vacuum the dust created by the grinding operation. In order to improve the vacuum performance, a rubber curtain was added to the grinder as shown in Figure 3(c). It was hoped that the dust collection would be improved by enclosing the grinder with the rubber curtain. For further removal of the dust residue, a brush was installed at the back of the machine. Even after these efforts, it was found that an extra power source needs to be added to make the dust collection mechanism function satisfactorily. The enhancement of the vacuum pump's vacuuming power will be made in the next version of the concrete surface grinding machine.

4. Remote control for concrete surface grinding

Operation of the existing concrete surface grinding machine relies heavily on an operator's skill, and even on the physical ability to handle heavy equipment. The dynamic nature of this operation makes it more feasible to apply an interactive control for the machine (Moon, Bernold 1997). A wireless remote controller was developed to remotely control the machine. Assisted by the remote controller, the operator can move the machine back-and-forth, change the direction, change the speed, and adjust the grinding depth within a range of 1 km away from the machine. The computer-assisted environment provides functions for: 1) path planning, 2) wireless joystick control, 3) machine tracking, and a 4) graphical operator interface. This section explains the remote control scheme and the developed system components for the tele-operation of the concrete surface grinding machine (Fig. 5).

First, path planning provides a moving path for the grinding machine in the work area. A profile-meter provides data on the bottom surface of the concrete pave-

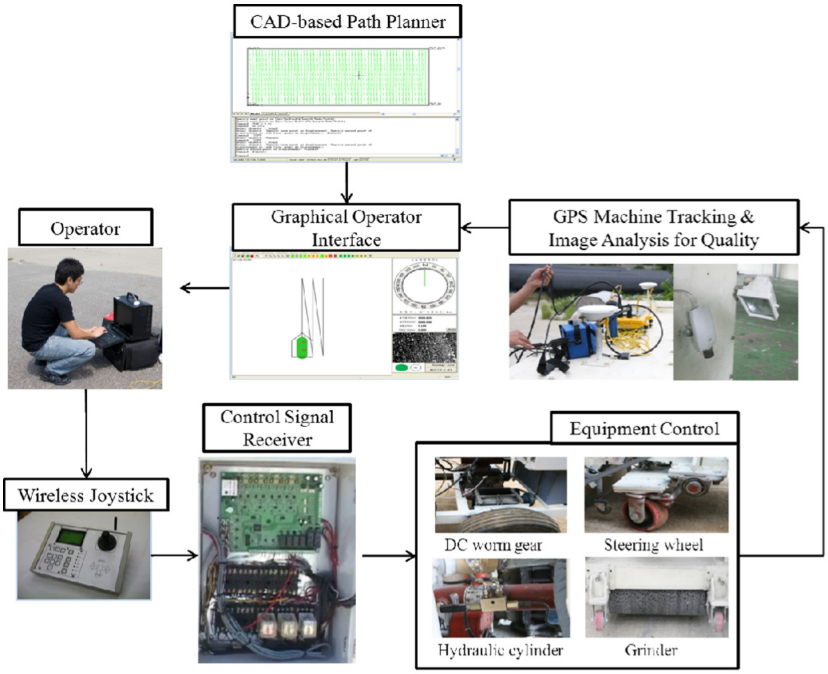


Fig. 5. Remote control system structure and components

ment to be used in the path planning. Based on this information, the operator can select the areas that require the grinding work. The path planner, developed in an AutoLisp environment, then generates a work plan to grind the uneven surfaces. When the surface grinding covers the entire surface area of the concrete pavement, the path planner can identify minimum travel distance using the field-surveyed CAD data (Moon *et al.* 2010).

Second, a wireless joystick control is utilized to generate control commands for the operation of the surface grinding machine. A joystick was developed so that the operator can transmit the control command to the machine at a distance from the work area. The device functioned as a wireless communication system for the back-and-forth movement and rotation of the machine during the operation. The joystick was also used to generate a command to adjust the height of the grinder. The transmitter in the device sends remote command signals wirelessly to the receiver installed on the machine, which in turn modulates the signals into a control signal for the DC motors and hydraulic cylinders as shown in Figure 5.

Third, machine tracking is used to locate and track the position of the concrete surface grinding machine in real time. The Real-Time-Kinematics (RTK) GPS has a reference station apart from the GPS antenna, and has centimetre-level accuracy (Trimble 2003). The GPS rover station consists of two antennas, a GPS receiver, a receiving radio modem, and wireless communication device to send location data to the control computer. The GPS receiver receives GPS signals via the antennas and calculates the location as well as the direction of the machine. The position data from the GPS is in an absolute coordinate and is converted into a relative position (Moon *et al.* 2010). The direction (orientation) of the concrete surface grinding machine is identified using two GPS antennas that were installed on the top of the machine. The location information sent by the GPS receiver to the control computer was converted into visual information to enable the operator to monitor the status of concrete surface grinding in real time.

Fourth, a graphical operator interface (GOI) provides an interactive display of the location and speed of automated equipment overlaid on the planned path. The approach taken for the GOI in this study is a passive type as discussed by Seo *et al.* (2000) in that the GOI provides an interactive display of the location and speed of the concrete surface grinding machine overlaid on the planned path rather than being used for generating commands for machine operation. As shown in Figure 5, the left side of the interface shows the main screen with the enlarged view of the planned path and the machine. The shape of the machine has been simplified for clarity. The work progress is displayed with a thicker line. The upper right corner window shows the orientation of the equipment. When the equipment deviates from the planned path, the operator can alter the path using the wireless joystick to make the machine return to the planned path.

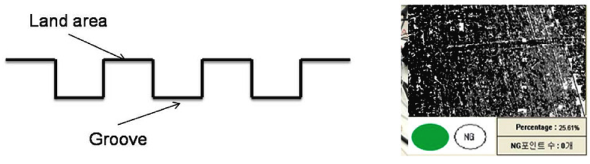
5. Quality control for concrete grinding

The attempt at remote-control for concrete surface grinding requires the capability of real-time quality inspection to evaluate grinding work. In response to this functional requirement, the prototype utilizes digital image processing for the measurement of quality from a distance. The technology implemented used a digital network camera that was placed at the back of the concrete surface grinding machine (Fig. 6(a)). The camera takes pictures of the ground surfaces and sends them to the host computer via Ethernet using the Internet protocol. A computer processing unit embedded in the camera is able to compress the picture images into various file formats (e.g. JPEG, etc.) to reduce transmission time (Fig. 6(b)).

The host computer then executes image processing to evaluate ground surface quality. Figure 6(c) describes the enlarged sectional shape of the concrete surface ground by diamond blades (FHWA 2006). This sectional shape has two areas of distinguishable texture. The prominent part is the land area, and the depression part the groove area. As Sezgin and Sankur (2004) discussed, the image-threshold technique can be applied to distinguish between the background and objects. From a threshold analysis, these two areas could be separated into black-and-white binary images based on a selected pixel value (0–255). Then, the amount of pixels that represent the groove area in an image is quantitatively calculated in order to perform a remote quality-inspection based on the percentage of the pixels. In the lower right corner of the graphical operator interface screen, the color of the quality indicator turns to green when the quality meets the criteria, otherwise a yellow color is displayed as shown in Figure 6(d). The results of image processing were associated with the GPS data to identify and indicate the areas that need rework to improve quality.

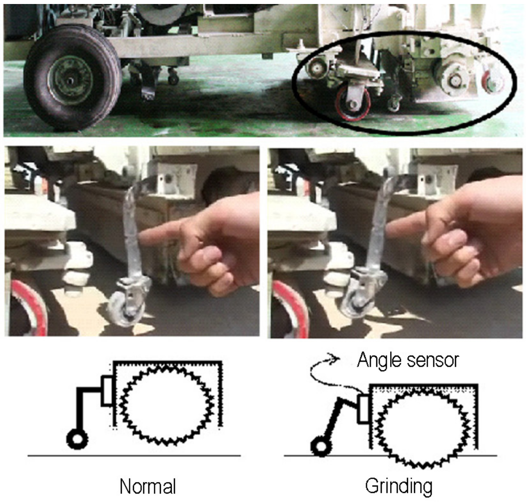
The grinding machine needs to maintain the grinding depth for quality control. With a manually-operated machine, the grinding depth is checked by the operator based on visual inspection of the ground surface as well as from the grinding sound. In a remote-control situation, as the operator is at a distance from the machine, an

(a) Network camera (b) Convertor



(c) Prominence and depression on cut surfaces (d) Quality inspector

Fig. 6. Image processing devices and quality inspection



(a) Angle sensor and its operating concept

(b) Setting design level

Fig. 7. Angle sensor for quality control

angle sensor was installed in front of the grinder to set and monitor the grinding depth as shown in Figure 7(a). As the grinder is lowered by the hydraulic cylinder, the resistance value of the angle sensor is increased. The remote controller stores the electrical resistance value of the angle sensor for the desired grinding depth in memory (Fig. 7(b)) so that the controller sends a correctional signal if the resistance value deviates. The angle sensor used in this research has a less than 1 mm error range.

6. Performance test and evaluation

The remotely-controlled surface grinding machine was prototyped combining hardware and software technology. The prototype was deployed at actual concrete pavement sites to test its performance. The performance of the machine was evaluated using performance criteria to evaluate whether the prototype improved the existing manual practice and to identify any limitations in the current prototype and necessary future enhancements.

6.1. Field experiment

A total of 13 tests were done regarding concrete pavement surface grinding in the course of the prototyping. The tests focused on evaluating the performance in terms of the performance criteria developed during the functional requirement analysis. Figure 8 shows the prototype and the accompanying remote-control devices at one of the testing sites.

Fig. 8. Prototype performance tests

6.2. Safety evaluation

6.2.1. Worker health and physical hazards

The concrete dust that is generated during concrete surface grinding can negatively affect human health. The noise of the grinding operation is also a concern for an operator of existing manually-operated machines. The prototype's remote-control capability keeps the operator at a distance from the working area to protect the worker's health. An anti-collision module was also implemented to promote a safer working environment for the remote control concrete surface grinding. The module used ultrasonic sensors which are attached to four sides of the machine. These sensors can detect any objects approaching the machine during the operation. The module was designed to activate an alarm at a 2 m safety distance. This type of collision avoidance is important in actual deployment of the machine for increasing operation safety.

6.2.2. Environmental pollution

The concrete dust that is generated during concrete surface grinding has an impact on both the operator's health and environment. Therefore, the performance of the dust collector is important in preventing pollution to the site and the surrounding area. This performance was measured by considering the amount of dust residue on the concrete surface after the grinding operation. By comparing the weights of dust residue with and without the dust collector, it was found that about 70–80% of the dust could be removed with the dust collector. Some amount of dust residue remained on the ground surface after the operation. It is estimated that the power of the vacuum pump was insufficient to completely collect the dust because the power of the diesel engine was shared with the grinding operation. Additionally, the filter occasionally became clogged and weakened the collection performance. Therefore, the next version of the prototype should adopt a high-powered vacuum pump, probably using a separate power source solely assigned to the vacuum pump, and a filter with multiple layers to effectively collect the dust.

6.3. Quality evaluation

6.3.1. Maneuvering accuracy and grinding depth

Maneuvering accuracy significantly affects the quality of the grinding operation because any positioning error of the grinder results in either overlapping of the grinded path or missing of a portion of the concrete surface in between the grinding paths. The RTK GPS has a certain degree of position error. According to the technical specifications of the GPS device in our research, the positioning errors are within 2 cm in the horizontal direction and 3 cm in the vertical direction (Trimble 2003). This may cause the GPS position to jump around in the x-y plane with 2–3 cm maximum errors. This positioning error was acceptable because the path overlapping is allowed up to 50 mm according to a FHWA guideline (FHWA 2006). Therefore, the prototype can be effectively controlled by adjusting the blade width in path planning.

For example, the prototype used a 65 cm blade in the field test. If the width of a diamond blade is reduced in path planning, the path will overlap by as much as the reduced width in actual field application. This control scheme reduces the chance of missing a portion of concrete pavement or overlapping by more than 50 mm. Since GPS errors are normally distributed, unacceptable directional errors were also avoided (Moon *et al.* 2010). The grinding depth was controlled by lifting and lowering the grinding blade with the hydraulic cylinder along with the angle sensor that sets and monitors the grinding depth. The grinding depth was set successfully with the angle sensor before grinding. Although the angle sensor data produced noise caused by the vibration once the grinding operation starts, it was within an acceptable level. In addition, over-grinding was avoided by installing a separate set of wheels that limit the grinding depth.

6.3.2. Quality check capability

The image processing module for quality inspection should make a decision as to whether or not to accept the ground surface. There are, however, two types of errors to be considered in the quality inspection: 1) when actual quality is OK, the quality controller may judge that it is not acceptable; 2) when actual quality is not OK, the quality controller may judge that it is acceptable. The quality is judged based on the percentage brightness of an acquired image (i.e. the percentage of the white pixels after thresholding as explained previously). Three hundred sample images were analyzed with respect to the criteria of brightness or the quality criteria. After a series of analysis, it was found that the quality criteria of 16.5 percent in brightness gave the best results. The results shows that the number of errors with a judgment of acceptance in the faulty area is less than 10%, and the number of errors where the judgment is to reject in the ground area is about 5%. It was observed by the authors that the major source of errors in the quality check was due to the dust residue inside the groove of the grinded surface because the image analysis looks for the existence of the grooves as evidence of the grinding. It is therefore expected that these errors would be reduced by eliminating the dust residue.

6.4. Productivity evaluation

6.4.1. Grinding and maneuvering speed

The concrete surface grinding machine should be able to move for both positioning and surface grinding. When positioning, the machine uses two DC motors. Additionally, the steering wheels did not fail during the entire series of tests and showed stable control performance.

Machine speed directly affects productivity during surface grinding. The tests show that a remotely-controlled operation did not significantly contribute to productivity improvement compared to conventional manual operation in concrete surface grinding. The productivity of the remote operation was found to be slightly better than the conventional approach. The grinding speed of the prototype was increased, but the maneuvering speed for re-positioning was decreased compared to the existing manually-operated machine method. Considering the grinding operation and the re-positioning of the machine together, the daily production of the conventional operation was improved about 8.3% by employing the remotely-controlled prototype (Moon *et al.* 2010).

Although the developed prototype showed improved productivity, the following disadvantages of the prototype in terms of the productivity were observed. A conventional operation uses water to reduce the resistance force between the cutter and the concrete surface as well as to keep dust under control, but the prototype in this study does not use water. This dry grinding method caused a number of disadvantages resulted in high torque and load on the engine. The cutter heads also needed a cooling period to reduce wear-and-tear, thus reducing the productivity of the grinding work.

6.4.2. Path-planning capability

The path-planning capability of the prototype proved to be a tremendous advantage over the conventional manual operation. It should be emphasized that the conventional operation of concrete surface grinding largely depends on an operator's skill. The remote control, however, utilizes both the operator's skill and the capability of the electronic controller that maintains constant speeds and grinding depth along the predefined path. The path created by the path planner provides an efficient grinding path that can reduce changes in direction thus reducing the operation time compared to that of inexperienced operators. This approach also helps improve the quality of concrete surface grinding compared to the conventional approach. Possible re-work by an inexperienced operator in the conventional operation may easily result in much worse productivity.

6.4.3. Economic analysis

A successful application of automation needs to be economically feasible. A simple economic analysis has been conducted to understand if the remotely-controlled machine is economically feasible for a concrete surface grinding operation. The comparative analysis of the conventional manual operation and the remote-control operation is done per 100 m^2 of a concrete surface. The cost is categorized in terms of machine costs and labor costs. The other costs of materials and expenditures are not considered because the difference does not significantly affect the total cost. In the manual operation, the machine costs 50,000,000 Korean Won (KRW). In the remote-control operation, it costs approximately 30,000,000 KRW to retrofit the machine for the remote-control feature. The conventional operation is usually executed by a team of one machine operator (labor cost: 112,268 KRW/8 hour) and one laborer (labor cost: 105,826 KRW/8 hour) (KPRC 2014). The remote-control operation is executed only with a machine operator. The manual operation has a productivity of 7.2 m^2/hour, and the remote-control operation has a productivity of 7.8 m^2/hour, according to a study conducted by Moon *et al.* (2010). The productivity and labor resource difference results in the cost savings of approximately 198,718 KRW/100 m^2. Therefore, the break-even point is obtained when the remote-control operation is applied to a surface grinding area as large as 15,096.7 m^2 by dividing 30,000,000 KRW with 198,718 KRW/100 m^2. For example, if a highway has four lanes with a total width of 14.4 m, the required length for the break-even point is 1,048.4 meters. The payback period is 0.93 years based on the 8 hour work per day, 260 day per year. In addition, the proposed remote operation can protect the health of the laborer and the operator by separating them from the dust created by grinding the concrete surface. With the growing concern on the workers' health, the estimation on the labor cost for the harmful conventional operation may be increased, which makes the proposed remote operation economically more feasible.

Conclusions

Currently, the construction industry is hampered by a shortage of skilled workers. The operation of concrete surface grinding is not an exception. A lack of skilled workers can result in poor ground surface quality and a high likelihood of injuries caused by overexertion and safety accidents. Additionally, the hazardous working environment during the operation can affect an operator's respiratory health and cause environmental pollution. To overcome these challenges, this study presented a prototype of a remotely-controlled machine for automated concrete surface grinding.

The prototype was able to support a remote operation of concrete surface grinding. The prototype was designed to be able to execute the commands from the operator as well as from the embedded control functions. To execute the machine commands, the software and hardware components of the prototype included state-of-art technologies in path planning, machine position tracking, a graphical operator interface, dust collection, and quality inspection. These technologies allowed the operator to be at a distance from the hazardous concrete surface grinding work area. The performance test proved that the prototype can provide the desired performance in machine driving, concrete surface grinding, dust collection, surface quality, and operator safety.

Further research is necessary to improve system performance of the prototype in terms of curved path planning, self-control, and dust collection. The commercial version of the prototype should enhance grinding performance by adopting a cooling device and additional power supply. The technology proposed in this study is expected to provide the base knowledge necessary for various types of automation such as for earth-moving equipment, pile work, cranes, concrete pumps, and dredging machinery. Additionally, the prototype can be modified and extended to develop an automated machine for the operation of pavement grooving. Such an attempt will ensure that the operator works in a safer working environment and improves the effectiveness of concrete surface grinding.

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References

A-core Inc. 2014. *Concrete grinding and grooving* [online], [cited 1 May 2014]. Available from Internet: http://www.a-core.com/Page.aspx/concretegrinding-grooving

Bernold, L. E. 2007. Control schemes for tele-robotic pipe installation, *Automation in Construction* 16(4): 518–524. http://dx.doi.org/10.1016/j.autcon.2006.09.002

Cousineau, L.; Miura, N. 1998. *Construction robots: the search for new building technology in Japan*. Reston, VA: ASCE Press. 130 p.

DOT Diamond Core Drilling Inc. 2014. *Deck grooving* [online], [cited 1 May 2014]. Available from Internet: http://www.dotdrilling.com/html/deckgroovingC.html

Federal Highway Administration (FHWA). 2006. *Concrete pavement rehabilitation guide for diamond grinding*. USA, FHWA. 22 p.

Haas, C. T.; Kim, Y. S.; Greer, R. 1997. A model for imaging assisted automation of infrastructure maintenance, in *The 2nd International Conference on Imaging Technologies: Techniques and Applications in Civil Engineering*, 25–30 May 1997, Davos, Switzerland, 108–117.

Kangari, R.; Yoshida, T. 1989. Prototype robotics in construction industry, *Journal of Construction Engineering and Management* ASCE 115(2): 284–301. http://dx.doi.org/10.1061/(ASCE)0733-9364(1989)115:2(284)

Kim, D.; Kim, J.; Lee, K.; Park, C.; Song, J.; Kang, D. 2009. Excavator tele-operation system using a human arm, *Automation in Construction* 18(2): 173–182. http://dx.doi.org/10.1016/j.autcon.2008.07.002

Korea Price Research Center (KPRC). 2014. *Standard labor cost in Korea* [online], [cited 1 May 2014]. Available from Internet: http://kostat.go.kr

Kunigahalli, R.; Skibniewski, M. 2008. Automation in concrete construction, in E. G. Nawy (Ed.). *Concrete construction engineering handbook.* Chapter 18. CRC Press, 18-1–18-17. http://dx.doi.org/10.1201/9781420007657.ch18

Kunigahalli, R.; Russell, J. S.; Skibniewski, M. J. 1994. Motion planning for automated construction, *Automation in Construction* 3(1): 71–78. http://dx.doi.org/10.1016/0926-5805(94)90034-5

Moon, S.; Bernold, L. 1997. Vision-based interactive path planning for robotic bridge paint removal, *Journal of Computing in Civil Engineering* ASCE 11(2): 113–120. http://dx.doi.org/10.1061/(ASCE)0887-3801(1997)11:2(113)

Moon, S.; Yang, B.; Kim, J.; Seo, J. 2010. Effectiveness of remote control for a concrete surface grinding machine, *Automation in Construction* 19(6): 734–741. http://dx.doi.org/10.1016/j.autcon.2010.03.001

PDWorld. 2014. *Conjet robot assisted with Guri Dam spillway repairs* [online], [cited 1 May 2014]. Available from Internet: http://www.pdworld.com/default.asp?categoryID=35

Sasaki, T.; Kawashima, K. 2008. Remote control of backhoe at construction site with a pneumatic robot system, *Automation in Construction* 17(8): 907–914. http://dx.doi.org/10.1016/j.autcon.2008.02.004

Seo, J.; Haas, C.; Saidi, K.; Sreenivasan, S. 2000. Graphical control interface for construction and maintenance equipment, *Journal of Construction Engineering and Management* ASCE 126(3): 210–218. http://dx.doi.org/10.1061/(ASCE)0733-9364(2000)126:3(210)

Seo, J.; Haas, C.; Saidi, K. 2007. Graphical modeling and simulation for design and control of a tele-operated clinker clearing robot, *Automation in Construction* 16(1): 96–106. http://dx.doi.org/10.1016/j.autcon.2005.12.002

Sezgin, M.; Sankur, B. L. 2004. Survey over image thresholding techniques and quantitative performance evaluation, *Journal of Electronic Imaging* 13(1): 146–168. http://dx.doi.org/10.1117/1.1631315

Shin, D. H.; Han, D. H. 2003. Open-loop velocity control of concrete floor finishing robots, *Journal of Intelligent and Robotic Systems* 36: 285–300. http://dx.doi.org/10.1023/A:1023037004444

Skibniewski, M.; Hendrickson, C. 1990. Automation and robotics for road construction and maintenance, *Journal of Transportation Engineering* ASCE 116(3): 261–271.

Skibniewski, M. J.; Kunigahalli, R.; Russell, J. S. 1993. Managing multiple construction robots with a computer, *Automation in Construction* 2(3): 199–216. http://dx.doi.org/10.1061/(ASCE)0733-947X(1990)116:3(261)

Surface Systems and Instruments Inc. 2014. *High speed profiling systems* [online], [cited 1 May 2014]. Available from Internet: http://www.smoothroad.com/products/highspeed/

Tang, X.; Yamada, H. 2011. Tele-operation construction robot control system with virtual reality technology, *Procedia Engineering* 15: 1071–1076. http://dx.doi.org/10.1061/(ASCE)0733-947X(1990)116:3(261)

Trimble. 2003. *MS Series operation manual*. Trimble Navigation Limited Geomatics and Engineering Division, Dayton, Ohio, USA. 1023 p.

Van Osch, M.; Bera, D.; Van Hee, K.; Koks, Y.; Zeegers, H. 2014. Tele-operated service robots: ROSE, *Automation in Construction* 39: 152–160. http://dx.doi.org/10.1016/j.autcon.2013.06.009

Yamada, H.; Tao, N.; Dingxuan, Z. 2008. Construction telerobot system with virtual reality, in *2008 IEEE Conference on Robotics, Automation and Mechatronics*, 21–24 September 2008, Chengdu, China, 36–40. http://dx.doi.org/10.1109/RAMECH.2008.4681331

Zhou, Y.; Skibniewski, M. J. 1994. Construction robot force control in cleaning operations, *Journal of Aerospace Engineering* ASCE 7(1): 33–49. http://dx.doi.org/10.1061/(ASCE)0893-1321(1994)7:1(33)

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