Master's Thesis

IIoT-Enabled Manufacturing Process Monitoring and Resource Positioning

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Abstract

Scheduling and planning are the central functions to increase the productivity in manufacturing. In a shop floor, these functions should be deployed in a real-time manner by considering the dynamic conditions of manufacturing processes. In this regard, the prerequisite is seamless manufacturing process monitoring to acquire live workplace data. Manual data acquisition by experienced workers can provide a reliable process report at low cost. However, this may shoulder additional responsibilities of the current workload which can affect job performance in a negative way. Recently, industrial internet-of-things technology with advanced sensors and long-ranged telecommunication devices have enabled us to acquire high quality workplace data. Therefore, the objective of this study is to develop a manufacturing process monitoring system that provides two main functions: (i) a production progress monitoring and (ii) a manufacturing resource positioning. To do this, we first analyze a target manufacturing system and extract the key characteristics for production progress monitoring. We then discuss how to select the appropriate process data and determine the data acquisition method. Production progress is measured by comparing the acquired field data with the scheduled manufacturing plan. We estimate manufacturing resources positions and workspace by (i) analyzing the operation data of overhead cranes in a shipyard and (ii) interpreting correlation lags between acoustic signals obtained by multiple microphone sensors. The developed manufacturing process monitoring system is illustrated and demonstrated with the case study of ship block assembly monitoring.

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I. Introduction

1.1 Background

Scheduling and planning are the central functions to increase the productivity in manufacturing and manufacturing monitoring system stands for this demand. It analyzes the acquired workplace data and converts it into process information. This information can be used for manufacturing process monitoring, such as operator safety, fault diagnosis, and production progress. Among these, the production progress monitoring uses manufacturing information to identify the shop's status. This identification is used for the rescheduling for the following processes. On a shop floor, these functions should be deployed in a real-time manner, considering the dynamical conditions of the manufacturing processes. In this regard, seamless manufacturing process monitoring is needed to acquire live workplace data; hence, interest in the Internet of Things (IoT) has increased.

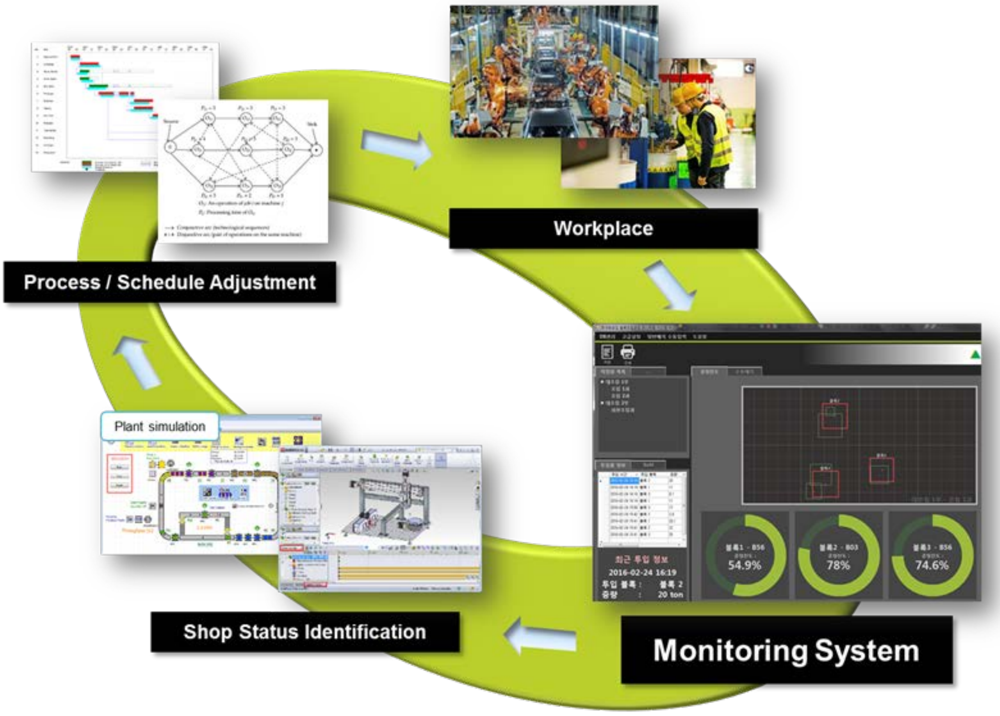

Figure 1.1: Job shop schedule feedback with monitoring system

The IoT is a novel paradigm that is receiving much attention from modern telecommunication studies. Foundational techniques originated from the Information and Communication Technology (ICT), like sensors, actuators, wireless telecommunication technologies, etc.; however, through the unique address scheme, the IoT-based devices are able to communicate and provide feedback to one another for accomplishing a common goal (Atzori et al. 2010). Recently, industrial fields such as transportation and manufacturing are expecting to advance based on the IoT. In the manufacturing field, growing interest for the Industrial Internet of Things (IIoT) especially focuses on data acquisition and feedback for manufacturing processes (Da Xu et al. 2014).

1.2 Motivation

In the flow-shop manufacturing environment, process data can be measured through adopting modules which can identify parts or products. The location where the data was acquired is the same as the location of the product. The acquired product ID and the location can be converted into Work-in-Process (WIP) data. In other words, the position of the product indicates the current process and it also can be converted into progress information. For this reason, adopting IoT technologies for the flow-shop is actively studied, just like the Radio Frequency Identification (RFID) case.

Different from the flow-shop, a project-shop or job-shop manufacturing environment carries various processes in a fixed position after site installation. Only with the positioning data, it has limit to measure the production progress. For example, the building industry represents the project-shop manufacturing. A building, which represents the product in this case, does not move from the beginning to the end of the construction. Hence, it is meaningless to apply RFID technology to the building per se, as it cannot give any meaningful data.

In this thesis, we selected a curved-block assembly shop-floor as a target manufacturing system to apply the process monitoring system. Due to the size of the product, many features are similar to the building case. However, the product sometimes moves to another workplace because of the spatial schedule. Delay of the product assembly can affect the workplace of another product. In this regard, the administrator should monitor not only the production progress but also the spatial state of the products.

1.3 Objective

To develop an appropriate process monitoring system for the curved-block assembly shop-floor; this system should have the production progress measurement method. At this point, we should consider the industrial characteristics of the shipbuilding industry. The shipbuilding industry produces a high value product. Sub-assemblies, which are produced in each shop-floor, also require a high cost. Since the cost to discontinue a process must also be considered in order to test and apply new monitoring methods, development of inefficient monitoring methods can significantly reduce productivity. In this regard, we should analyze the target shop-floor closely to find the most appropriate monitoring method.

In the production progress measurement, identification of the product is a prerequisite. A workspace produces multiple products at the same time. Without product identification, acquired data from the workspace cannot be classified for a single product. However, the curved-block assembly shop-floor does not save the spatial schedule to the database. From the basic features and the product ID in the database, we should match the field data to identify the product. For the grouping and matching between the field data and database, several positioning methods can be applied. Therefore, we studied and applied several positioning methods to solve this problem.

1.4 Outline of the thesis

This thesis consists of five chapters. Chapter 1 introduces the demand for the process monitoring system. In Chapter 2, literature surveys, which are contained studies of the process monitoring in industrial fields and several positioning methods, are presented. The developed progress monitoring method for the target shop-floor is described in Chapter 3, and the developed manufacturing resource positioning methods are described in Chapter 4. Lastly, the conclusions and future research are described in Chapter 5.

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II. Literature Survey

2.1 Progress monitoring

Over the past years, many methods have been developed in process monitoring area. Major objective of those researches is monitoring for the fault diagnosis (Venkatasubramanian et al. 2003). Most of the shop-floor has compact size for the production process and this is an advantage in monitoring the process environment. For this reason, production progress itself was not a difficult feature to collect. However, project-shop or job-shop manufacturing systems such as building or shipbuilding industry have had trouble with monitoring production progress. In this regard, we surveyed about traditional shop-floor first, building and shipbuilding is also surveyed.

2.1.1 Shop-floor

WIP (Work-in-process) management plays a critical role in manufacturing system. It controls the material and information flows, monitors the WIP level for each workstation/stock, tracks the statuses of each manufacturing object and the progress of each production order, and also responds to request form the ship floor (Qiu and Joshi 2000). Management and control facilities of shop-floor are required to implement real-time traceability, visibility and interoperability in improving the performance of shop-floor planning, execution and control by using workflow management architecture and RFID-enabled smart gateway (Zhang et al. 2011). Applying RFID reader on the shop-floor and giving ubiquitous devices to the operators can read real-time WIP information. Especially for the flow-shop manufacturing system, identification and positioning of the product are directly converted to the WIP information.

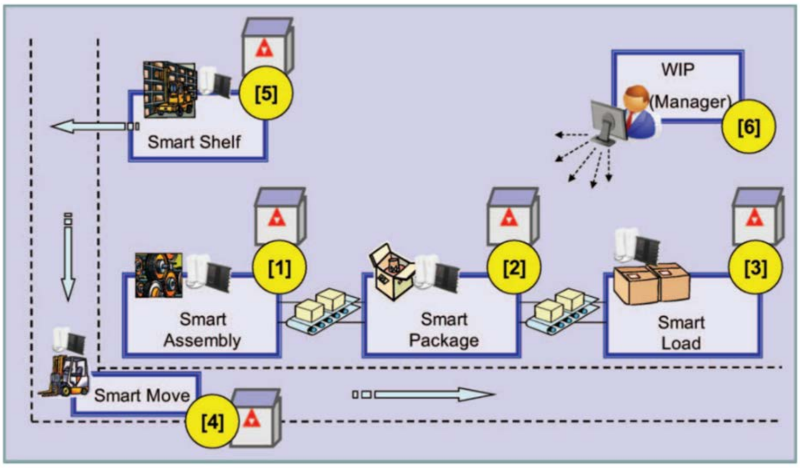


Figure 2.1: Overview of the motivating manufacturing shop floor (Zhang et al. 2011)

2.1.2 Building industry

Building industry is the representative of the project-shop manufacturing system. Delays are a very common and costly problem encountered during construction projects. To solve the causes that lies in unrealistic planning and unforeseen site conditions, automated activity tracking subsystem based on image recognition, automated material tracking subsystem, and a mobile computing supported communication environment are developed (Rebolj et al. 2008). In other related study, sparse reconstructed scenes superimposed over 4D models allow site images to be geo-registered with the as-planned components and consequently, location-based image processing technique to be implemented and progress data to be extracted automatically. The results of progress comparison between as-planned and as-built performances are visualized in the D4AR (4D Augmented Reality) environment using a traffic light metaphor (Golparvar-Fard et al. 2009).

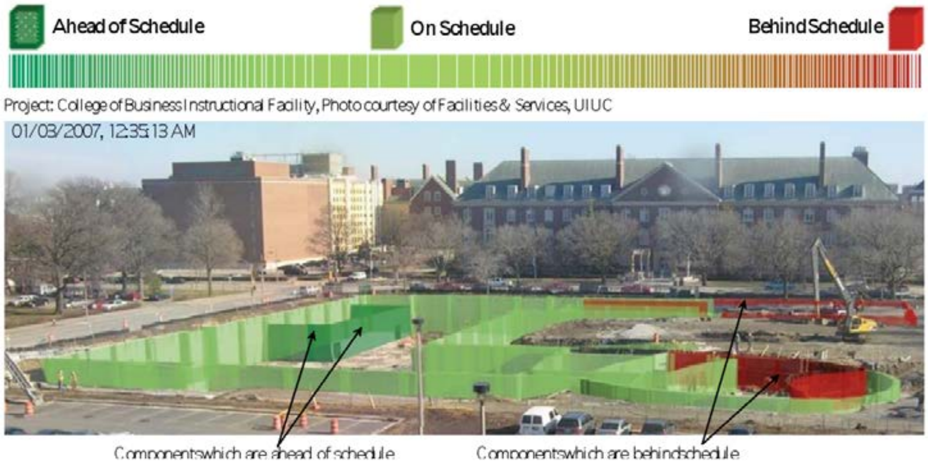


Figure 2.2: The as-planned 3D model of UIUC College (Golparvar-Fard et al. 2009)

2.1.3 Shipbuilding industry

Shop building is typically one-of-a-kind order production and also traditional labor-intensive assembly industry. In shipbuilding, there are several types of manufacturing process planning such as block division, assembly process planning, outfitting process planning, erection process planning, Numerical Control (NC) data generation. Among these process planning activities, the assembly process planning is by far important since it determines what happens in the other planning activities and also it takes more time to plan than all the others (Cho et al. 1996). Each curved-block is assembled in a fixed position like a building industry. Assembled blocks are stocked at a yard and transported to the dock for the final assembly. However, blocks are not always located in a fixed position from start to end. As spatial schedule changes, blocks are rearranged for the spatial efficiency. The principle workspace is defined, but it also interferes other workspace depending on the shape of a block.

To monitor this harsh environment, a sensor-based remote monitoring technique for the ship block assembly is studied. Instead of manual processing or optical measuring devices, the proposed approach attaches some distance-measuring sensor nodes to ship blocks. Remote monitoring of the assembly status makes it possible to minimize marginal errors during ship block assembly process, and helps efficient ship building (Lee 2009).

In other study, the tracking and monitoring system for the curved plates forming process with shop level using RFID is designed. RFID tag is attached on the raw material of the block, metal plate in this case. During the plate forming process, absence of the material affects to the schedule in negative way. To figure out absence of the plate and analysis, a prototype of the system has been implemented with hardware and application software (Noh and Shin 2009).

Welding process is one of the weight process in ship block assembly process. A method for differentiating fitting and welding using the current values obtained from the welding machine is developed. This current data of welding used to develop a method of identifying the work progress of blocks through a correlation equation between the welding length and arc time of the block (Ahn et al. 2011).

The vision-based technology has been widely used for inspection in various area. Especially like a building industry case as described in previous survey, construction process has several limitations to adopt other monitoring methods. Ship block assembly has similar characteristics with building industry that it should be called construction rather than assembly. Focused on this characteristics, vision-based system for monitoring block assembly is proposed. The images acquired from the camera are subsequently processed to extract the areas of the blocks. Next, the extracted blocks are identified and compared with CAD data for estimating the assembly progress. The estimated information is provided to the operator for efficient management of the block assembly schedule (Kim et al. 2015).

Figure 2.3: Filtering process of the ship-block image (Kim et al. 2015)

2.2 Wireless indoor positioning algorithm

Local positioning systems are able to track physical assets or people. Such systems can help, but are not limited to, factory automation, asset management. However, it is not easy to apply such systems at the factory level because they are limited by the challenging environment (e.g., obstacles and hostile environment). Advanced wireless technologies provide a chance to make such applications possible (Chan 2010).

It is not easy to model the radio propagation in the indoor environment because of severe multipath, low probability for availability of line-of-sight (LOS) path, and specific site parameters such as floor layout, moving objects, and numerous reflecting surfaces. There is no good model for indoor radio multipath characteristic so far (Pahlavan et al. 2002). Except using traditional triangulation, positioning algorithms using scene analysis or proximity are developed to mitigate the measurement errors. Targeting different applications or services, these three algorithms have unique advantages and disadvantages. Hence, using more than one type of positioning algorithms at the same time could get better performance (Liu et al. 2007).

2.2.1 Triangulation

Triangulation is a method which uses a geometric properties of triangles to estimate the target position. It can be classified in two categories, lateration and angulation. Lateration considers the distance between the reference and target to estimate position. So, it is also called range measurement techniques. Instead of measuring the distance, directly using Received Signal Strength (RSS), Angle of Arrival (AOA), Time of Arrival (TOA), and Time Difference of Arrival (TDOA) are usually measured. In case of TOA and TDOA, distance is calculated by multiplying velocity of signal and travel time. Angulation measures the angle between multiple references and target is the angulation such as radar. Through calculating contact point of each direction, target position is estimated.

TOA

TOA is also called as Roundtrip Time of Flight (RTOF). Defining roundtrip time of the signal from transmitter to receiver, target position must be relied on the line circle that has diameter equal to distance. Overlapping two circle can give possible two substitute point and by adding one more receiver, target position can be clearly estimated as described in the Figure 2.4. However, this roundtrip method has synchronization problem. Knowing the time of arrival means it already know the time of signal transmitted. Synchronization between the target position and the receiver is prerequisite of the TOA method. In case of identifying unknown signal source, this method cannot be applied.

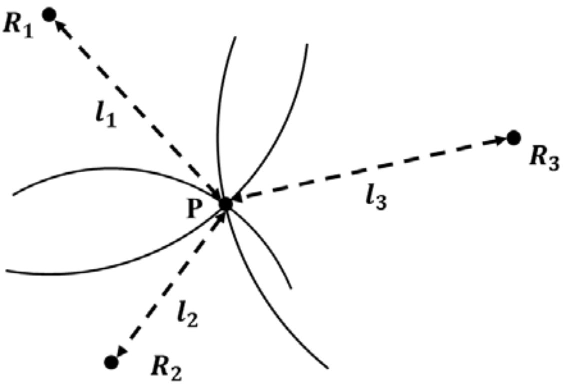


Figure 2.4: Positioning based on TOA measurement

TDOA

The idea of TDOA is to determine the relative position of the mobile transmitter by examining the difference in time at which the signal arrives at multiple measuring units, rather than the absolute arrival time of TOA. Different with the TOA, time synchronization between the target and receiver is not needed but each receiver should be synchronized. Similar with the circle from the TOA, TDOA can give the hyperboloid possibility of the target position. Overlapping those hyperboloids can give the position estimation result.

Moreover, direction of the sound source can be estimated with TDOA method. When a distance between the receivers and the target is quite far, direction can be geometrically calculated. To mapping the position on the 2-dimensional space, calculating contact point between the target plane and the directional vector. However, for the 3-dimentional mapping, additional method is needed. In the surveyed studies, a method using both TODA and Doppler model to mapping the target which located far from the receiver (Basiri et al. 2012).

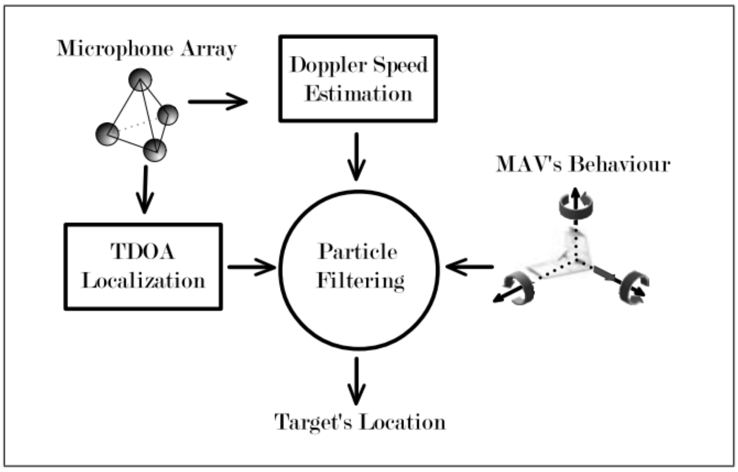


Figure 2.5: Schematic diagram of the TDOA and Doppler speed estimation (Basiri et al. 2012)

RSS

There are some disadvantages to the above two methods. In indoor environments, it is difficult to find the Line-of-Sight (LOS) channel between the transmitter and the receiver. Propagation in this environment would suffer from multipath effects. The time and angle of the signal are affected by the multipath effect. Therefore, the accuracy of the estimated position can be reduced. Another approach is to use the attenuation of the emitted signal strength to estimate the distance of the mobile device in some measurement unit sets. The signal attenuation based method attempts to calculate the signal path loss due to propagation (Liu et al. 2007). Due to severe multipath fading and shadowing present in the indoor environment, path-loss models do not always hold. The parameters employed in these models are site-specific. The accuracy of this method can be improved by utilizing the premeasured RSS contours centered at the receiver or multiple measurements at several base stations (Zhou et al. 2005).

AOA

The central observation suggesting that positioning using AOA is possible is that the following: if we know the positions for the vertices of a triangle and the angles at which an interior point “sees” the vertices, we can determine the position of the interior point. This problem, called triangulation, is somewhat similar to the trilateration problem, used in Global Positioning System (GPS) (Hofmann-Wellenhof et al. 2012). Similar with TDOA, the delay of arrival at each element is measured directly and converted to an AOA measurement. Several studies used AOA method for the ad-hoc positioning. A method for all nodes to determine their orientation and position in an ad-hoc network where only a fraction of the nodes have positioning capabilities, under the assumption that each node has the AOA capability is developed (Niculescu and Nath 2003).

III. The Production Progress Monitoring Method

3.1 Problem statement

Manufacturing monitoring systems must consider many aspects of manufacturing, such as maintenance of machines, operator safety, fault diagnostics, etc. Among them, production progress measurement is one of the basic functions that a monitoring system should have. Work in process with or without delays affects the remaining process. In this manner, when the production plan changes, the process manager should reschedule the remaining processes to improve productivity. Therefore, production progress should be monitored in real-time as fast as possible and the operator should be provided with as much accurate information as possible. However, installation and setup of a monitoring system requires multiple stages – preparation, installation, clean up, optimization, etc. – and several stages can cause discontinuities in the production process which can lead to economic losses (Zimniewicz et al. 2004).

- BOEING had introduced the BAAN-ERP system to monitor the whole production process in real-time. Tens of millions of dollars were invested in the project and employee education. However, decentralized departments had handled each process in different ways and this became a severe impediment to standardize the process management. In addition, education for the limited number of employees resulted in miscommunication between managers and operator.

As described in the example above, even if it costs a lot of money, training employees for a new system is also needed to reduce miscommunications. In this regard, when introducing a monitoring system, it is necessary to introduce an optimal solution that can sufficiently increase the productivity while considering the time and cost involved.

After the concept of the IoT was introduced, several studies have researched it to determine the advantage of using the IoT for manufacturing process monitoring. Through the communication between the monitoring modules, selection and acquisition of the appropriate data have become possible in diverse ways. In the case of the RFID, the ability to send and receive data packets of a small size enables the part or product to communicate with each other. On the other hand, due to the characteristic of radio frequency in that it is blocked by metals, it is difficult to adopt it in a metal-based manufacturing environment, such as the shipbuilding industry environment (Zhong et al. 2015). Similarly, even high-performance technology cannot be used in target manufacturing due to the incompatibility issues.

To construct the monitoring system with the appropriate IoT technology, it is necessary to precede the analysis of the characteristics of a manufacturing system. For example, for flow-shop manufacturing, the production progress can be measured by identifying the location of the work-cell where the product is processed. In the next step, the data acquisition method for the factors should be determined. In the case of the flow-shop described above, infrared proximity sensors are widely used to acquire the location for the work-cell where the product is processed. Finally, an estimation model definition for measuring the production progress is needed. As defined by the model, different progress results can be reported with the same data. Also, the weight coefficient decision should also be utilized for multiple data with different characteristics.

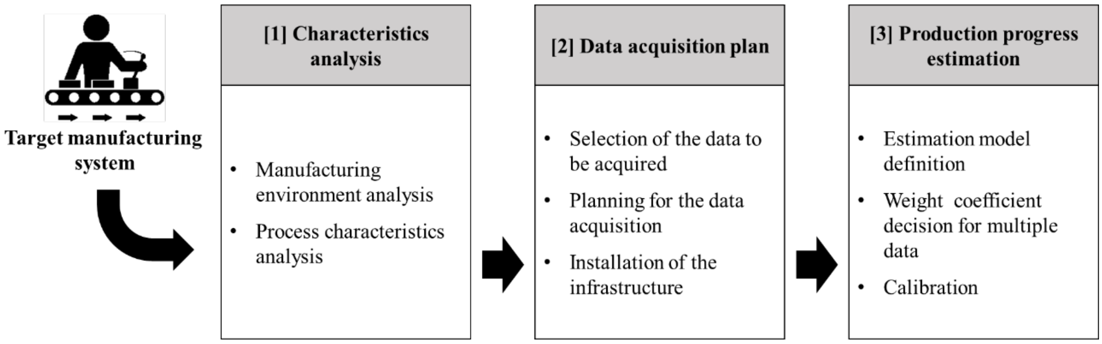


Figure 3.1: Framework for development of progress monitoring method

In this chapter, the production progress monitoring method will be described with the case study of the monitoring system for the curved-panel block assembly process in the shipbuilding industry. To make curved-panel blocks in shipbuilding, the pre-formed panels and the additional profiles are assembled on the height-adjustable pin jigs by laborious manual welding operations, described in Figure 3.2. For this reason, it is usually not easy to systemically control the block assembly process, which eventually hinders accurate assembly process planning and spatial scheduling (Stidsen et al. 1996).

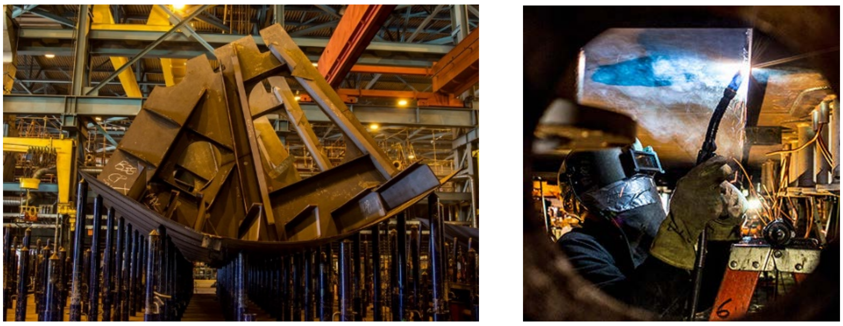


Figure 3.2: The shop-floor of a curved-panel ship block (Source: Politico Magazine)

3.2 Characteristics of the target manufacturing system

The catalog of data that can be selected for the production progress becomes more diverse as the characteristics of the manufacturing are analyzed. From the question of what is more important between quality and delivery to the small tool used for finishing process, the manufacturing process has various characteristics to be considered in a single stage. Taking all of this characteristics into account leads to efficiency problem. Therefore, process characteristics should be classified into several criteria.

3.2.1 Product, Process and Resource mapping

In ship block case, characteristics classified in PPR (Product, Process, Resource) mapping criteria (Schleipen and Drath 2009) (Cutting-Decelle et al. 2007).

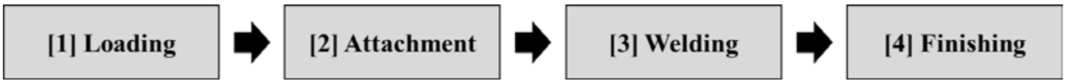
Product

Product not only means the finished but also parts or by-products. Internal characteristics like physical features of the product and external characteristics like the electronic compatibility both can be analyzed. However, curved-block assembly is volume expansion oriented process. So physical features such as weight, size, material, and etc. should be mainly considered. The main material is steel, but it also has some side parts made other materials such as plastic. Weight of the finished curved-block is tens or hundreds of tons and height of it is from a few meters to sometimes ten meters.

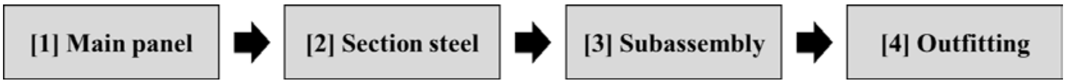
Process

Each curved-block needs constant space from the beginning to the end of the assembly process five or more days. However, due to the size of the facilities such as the overhead crane, expansion of the workspace is limited. To maximize the productivity, spatial scheduling for the workspace is preceded before the block assembly process. Each block has different the beginning and the end of the assembly process. So, spatial schedule is changed every day and change from time to time as production progress or team schedules.

After spatial scheduling, the block assembly is processed into major four stages as displayed in the Figure 3.3 (a) First, main panel is loaded onto pin jigs in the scheduled workspace. Onto the main panel, the following parts are loaded as sequence displayed in the Figure 3.3 (b) Welding operator aligns and fixes each loaded parts in a designed position with spot welding called ‘Attachment’. Continually, operators assemble parts through the welding line. Auxiliary parts and by-product of the welding is removed in the ‘Finishing’ process. In major four stages, loading and welding occupy largest portion of the assembly process. Therefore, those two process must be monitored first to measure the production progress.



(a) Main process of the curved-block assembly



(b) The loading sequence of a curved-block

Figure 3.3: The loading sequence of a curved-block

Resource

Resource means the elements that are needed in manufacturing process such as facilities, workplace, manpower, and so on. From the workplace to the small bolt, there is no limit in the definition of the resource. However, they are classifiable as static and dynamic resource depending on whether they are permanently fixed in the workplace or not. According to the classification, resources in curved-block job-shop can be classified as Table 3.2 below.

Table 3.1: Resources in curved-block shop-floor

Static Resource	**Dynamic Resource**
Pin Jig	Operator
Crane rail	Overhead crane
Wall or ceiling	Palette
Power source	Welding gun
⋮	Transport vehicle
	⋮

Using static resource for the process monitoring guarantees consistent data and is easy to maintain the module condition. Furthermore, the location of the resource itself can be a reference when acquiring spatial data such as distance or location. However, static resource is often considered a challenge in workplace expansion or in the installation of additional modules such as infrared sensors. On the other hand, using dynamic resource for the monitoring is free from space constraint. It is possible to collect data from a wide area by installing single module, and entire manufacturing process can be potentially monitored when dynamic resource participated in entire process. However, dynamic resource is maintenance-intensive and it is difficult to set reference than static resource when acquiring data. Pros. and cons. of each resource type summarized in the Table 3.2 below.

Table 3.2: Pros. and cons. of each resource type for process monitoring

Resource type	Pros.	Cons.
Static resource	• Easy to maintain • Easy to identify • Can be used as a spatial reference	• Passive data acquisition • Potential disturbance for the module expansion
Dynamic resource	• Widely cover the workplace • Positional flexibility	• Maintenance-intensive • Hard to identify • Hard to set and track reference

3.3 Planning for the data acquisition

From the analyzed characteristics, the information selection and planning for data acquisition steps follow. Reflecting all the characteristics can gather hundreds of data from the manufacturing process, but we have focused on the data that will be used to measure production progress. For example, the data that can be used for the fault diagnosis is also useful, but it is excluded if it does not helpful for the progress measurement. After selection and planning step, installation of the data acquisition infrastructure follows.

3.3.1 Selection of the information to be acquired

The data for production progress monitoring can be selected from both the product and the process characteristics. As process fluency, job-shop prefers the product characteristics because fixed position of a product helps stable data acquisition like characteristics of the static resource. On the other hand, flow-shop prefers process characteristics because it is hard to track a product that change position every moment in real-time.

Even key information for the production progress monitoring can be limited to acquire because of the internal-external conditions or the lack of technology. For example, video information gives visual data which can be used not only for the progress monitoring but also for overall manufacturing process management. On the contrary, video information can occur the security or operator rights issues, and it also needs much cost at initial installation or expansion. For this reason, the data selection step continues and confirm the final decision of the data at the end of the planning for the data acquisition step.

In the curved-block assembly, the data that can be used to measure progress of the loading and the welding process should be selected. Progress of the loading process can be measured using physical characteristics of the product. As the loading operation progresses, weight, shape and number of loaded parts of the curved block are expanded. As the welding operation progresses, welding rods, electric power and manpower are consumed. Compared to the loading operation, weight increase due to the welding operation is small, so it has been bypassed in progress measurement. To match the progress data with products, identification of each product should be preceded. Since the target workshop doesn't have computerized spatial schedule, identification data of product should also be acquired.

3.3.2 Planning for the data acquisition

Applying a method already tested and qualified at this stage gives reliable result to solve the problem. However, when the method that was useful in other process faces constraint at the target process, new method must be developed and this is the case in curved-block assembly process. In this case, planning for the new data acquisition method is needed. Prior to plan the data acquisition method, planning about reuse of the existing information collection method should be preceded. Afterward, manufacturing resources and methods which can gather target information are selected.

To measure the production progress of the curved-block, several studies was done in the shipbuilding industries. Research was carried out to develop the process management and monitoring system by providing personal devices and touch screen to the administrator (Seo 2013). Inspection of the experienced administrator can give reliable report at low cost. However, giving additional duty can give workload to the administrator and this effects job performance in negative way. Moreover, a minor mistake from the human can cause delay or confusion in the job schedule.

To reduce risks from the human resource, studies have been conducted to automate the process monitoring system. Adopting RFID technology at the flat-panel assembly line gives possibility for the assembly process monitoring automation (Lee 2009). RFID-readers located at each process check the position of a product. This method can be used for the sequential ordered process like flat-panel assembly line. However, in the curved-block case, due to the extended blocks assembly spaces according to the spatial schedule, it is difficult to plan the installation position of the RFID-reader. Furthermore, due to the frequent transfer and turn-over of the block, RFID-tag is at risk of being destroyed.

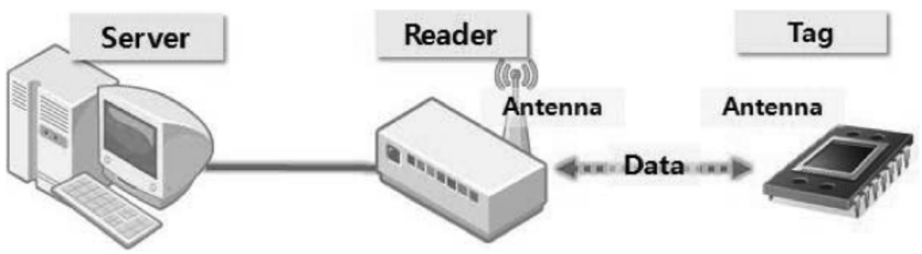


Figure 3.4: RFID System (Noh and Shin 2009)

Considering the site-installation characteristics of the curved-block assembly, we checked the researches of the building industry which is one of representatives of site-installation. In the building industry, vision information is used to monitor the progress of a building with image processing. Comparing acquired image with the CAD model measures reliable building progress (Rebolj et al. 2008). In the researches of curved-block assembly, production progress measurement of the block using vision information was studied (Kim et al. 2015). However, to capture the vision of the field, the location of the camera should move according to the spatial schedule. After camera moves near block, hull or huge part blocks line of sight in a single position.

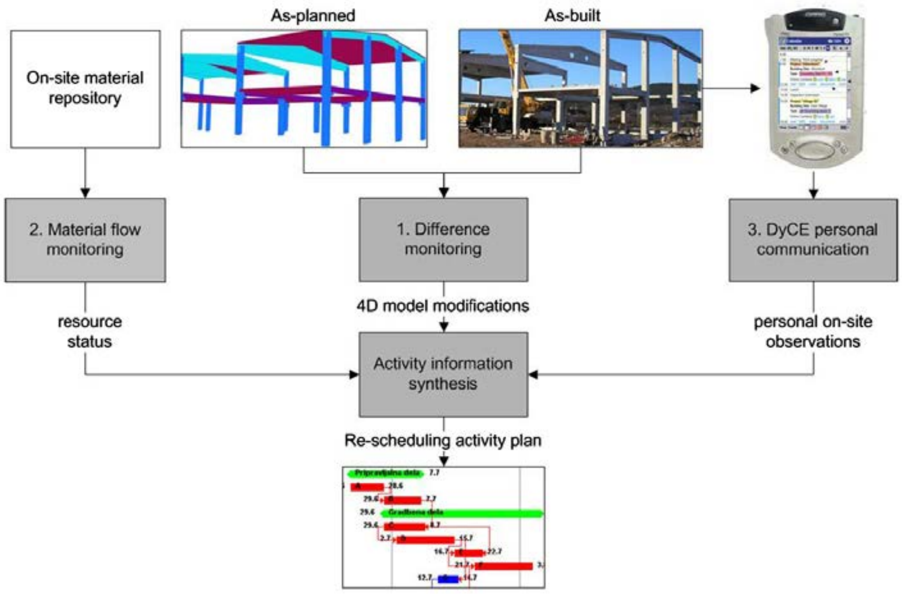


Figure 3.5: Conceptual scheme of the automated construction activity monitoring system (Rebolj et al. 2008)

Table 3.3: Target information and possible acquisition method for progress monitoring in curved-block assembly process

Process	Information	Acquisition method	Currently acquirable
Loading process	**Weight**	Pin jig, **Overhead crane**	√
	Shape	Depth camera, 3D scanner	
	Number of loaded parts	Overhead crane	
Welding process	**Electric power**	**Ammeter**, **Voltmeter**	
	Man power	Time in operation	√
	Number of used welding rods	Manual inspection	
Identification	**Part ID**	Camera, Manual inspection, **Overhead crane**	
	Product ID	Camera, Manual inspection	

As described above, the curved-block assembly process is limited to apply the existing methods due to the several characteristics. In this regard, a new method for data acquisition should be developed to measure the progress. To develop a new model for data acquisition, the target information and possible acquisition methods are summarized in Table 3.3. We also checked whether the information is currently acquirable or not.

Loading process

In loading process, weight, shape, and number of loaded parts are changed in loading operation processed. To check the change of the shape, visual information should be measured. To do this, visual equipment like depth camera, or 3d scanner are needed. However, the cost of the equipment installation is high. In addition, as described in the building industry case, the location of the camera should move according to the spatial schedule.

Weight can be acquired from pin jigs. All of the curved-blocks in the field are located and assembled on the pin jigs. Through adopting the weight-measuring equipment on the pin jig, weight change of the curved-block can be acquired. However, pin jigs are placed at intervals of one meter, and a single workspace has more than tens of thousands pin jigs. Installing and maintaining load-cells in all of those pin jigs needs time and cost similar to building a new workspace.

All of the parts which loaded in the curved-block are transported with the overhead crane. Using this point, total weight of the curved-block in field can be calculated from summation of the loaded part weights. And also number of loaded parts can be measured from analyzing the process of overhead crane. Appropriately, the overhead crane has been measuring the weight of the transported parts for legal reasons.

Welding process

Welding process has been estimated and measured based on the discretion of the operators and the inspectors (Ahn et al. 2011). Due to the often reworking of the welding operations, it is difficult to measure the exact welding progress by knowing the number of welding rods or the amount of welding deposit. Moreover, operators prefer to use their own welding machine on the wielding process, so acquiring electric power of the welding machine is also difficult to identify the operation it used. To solve this problem, identifying welding machine used for the operation and acquiring electric power is needed to check the welding progress.

Identification

Even the weight data of the parts is acquired through the overhead crane, the target block of the loading operation must be identified. After identification is done, the field data with schedule can be compared. We solved this problem with positioning method using driving information of overhead crane in the Chapter 4.1. Through grouping of the loaded parts in the operation, ID of each product is also measured.

3.4 Production progress measurement

Final goal of this chapter is estimating production progress which can be used to rescheduling and productivity improvement. To do this, we analyzed the manufacturing process and extracted the information which can be used for the production progress measurement. After that, selection of the information and planning for the acquisition method is processed. Finally defining a method for the production progress estimation is remained.

To estimate the production progress, predefined schedule and the field state should be compared. From the process information which gathered in prior stage, field state data can be extracted. Most manufacturing process save schedule in the database. In this regard, comparing data acquired from the field and data extracted from the database can give the basis of the production progress. So processing the field data fit with the data in database should be preceded before the comparison.

In curved-block case, a weight data in the database matched with the ID of each block. However, ID of the target block cannot be identified only with data gathered from the overhead crane. To fill the missing part, ID of the target block in this case, additional processing method should be developed. Scoring and grouping method is developed to estimate the ID of target block. This method needs loading position data of the overhead crane. The method for overhead positioning is described in the Chapter 4.1.

3.4.1 Scoring method for the single part identification

Comparing weight data between the database and the field can give the ID estimation. However, parts with the same weight can be loaded in one product or different products, so just comparing the weight can give wrong result. Furthermore, the actual weight of the part goes through several preprocessing steps and can be different with the estimated weight from the 3D CAD.

To solve this problem, scoring method scores the similarity between the actual weight and the database. The Gaussian distribution is used which the weight from the database is substituted as an average (μ) and proportion value of the weight is substituted as a standard deviation (σ). For distribution, reflecting the distribution of the field data with database was needed. However, to set the estimation method before the data acquisition, parts of the curved-block distribution is set in Gaussian distribution.

$$\frac{1}{\sigma\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Equation above is probability density function equation of the general Gaussian distribution. Through this equation, the field data can be measured in score compared with database. However, we changed the equation as below to reflect the 20% process error of the weight.

$$\frac{1}{\sqrt{2\pi}}e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$

Through the equation above, 9 tons at the field in 10 tons at the database has the same weight with 90 tons at the field in 100 tons at the database displayed at Figure 3.4 below. The result of the probability density function is calculated in percent (%), but for convenience of the expression, the result of the scoring method is calculated in score.

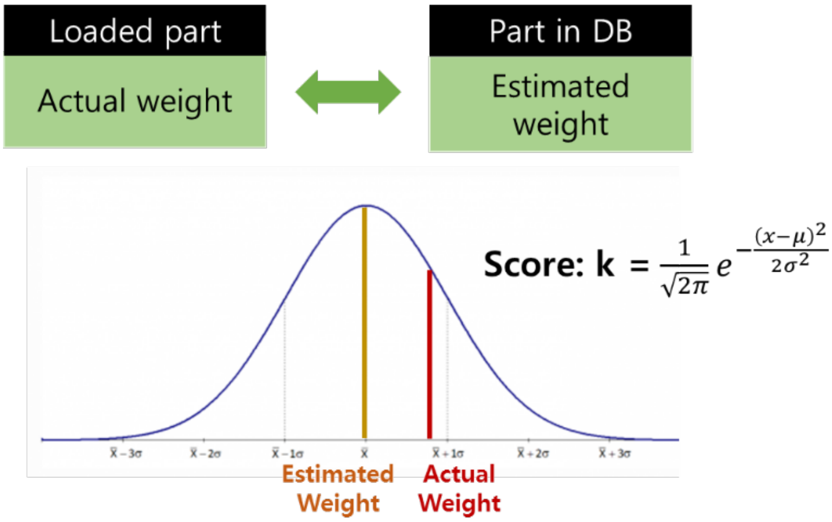


Figure 3.6: Scoring described in the probability density function

3.4.2 Grouping method for the product identification

After the scoring, grouping method is used to identify the target block. In the curved-block assembly workshop, a dozen cranes transport and load each part to each product without identification. For this reason, only with a single part, accurate identification has a limit. In case of the product, a group of the parts, more reliable identification is possible with the group of the scores.

From the positioning method described in Chapter 4.2, each product can gather the weight of the loaded parts without singular identification. Weight group of the loaded parts in the field block can be matched with the weight group of the database in the score matrix. For example, matching field block with 3 loaded parts and database block with 4 parts makes 3 by 4 matrix exampled in the Table 3.4.

Table 3.4: An example of block ID estimation

		DB Block i			
		DB sub1	DB sub2	DB sub3	DB sub4
Field Block j	Field sub1	S1	S2	S3	S4
	Field sub2	S5	S6	S7	S8
	Field sub3	S9	S10	S11	S12

From a single part scoring, similarity score between two blocks can be calculated with 3 steps.

i) A single score which has highest value takes the similarity pair (Field sub *n* – DB sub *m*)

ii) Eliminate the row and column of the similarity pair and rewrite the scoring matrix

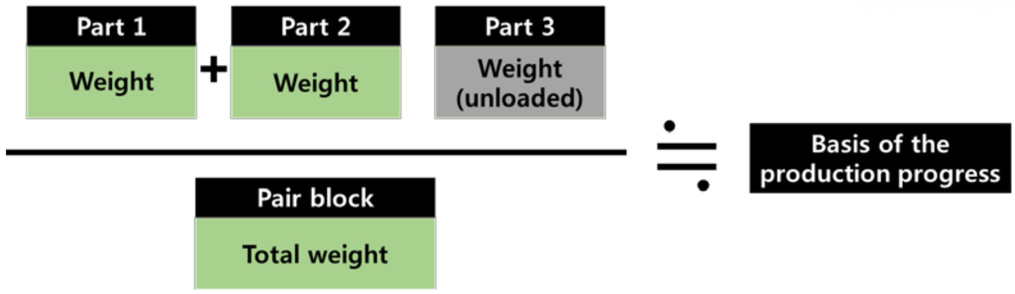
iii) Repeat the step i) and ii) until finding all similarity pair based on the number of filed subassemblies

After finding the similarity pair, each part in field block has its pair part in the database. An average score of all similarity pair using Euclidian distance becomes calculated similarity score between two blocks. In matching between two blocks, the block in database which doesn't have parts less than the field block is skipped. After matching all possible blocks, a block in database which has highest block-similarity score is the pair of a field block. Through this block grouping method, a field block can be identified using the Bill of Material (BoM) in the database.

3.4.3 Production progress measurement

Using the identified BoM of the similarity pair block in database, each field block can figure its assembly plan. Through this, scheduled total weight of the block and sum of the loaded-part weights can be calculated. Proportion of these two element constructs the basis of the production progress and it is displayed at Figure 3.5.

Based on this proportion basis, production progress can be measured by adopting another information. In curved-block case, simple proportion of the part weights alone cannot represent the exact loading progress. For example, heavier part can have a relatively small amount of welding line planned. It means that the production progress measured from the loading process needs calibration for the importance difference of each part.



$$\textit{production progress} \cong \textit{Progress\_Monitor}(\textit{actual progress in a real shop floor}, \textit{scheduled production plan}, \textit{calibration rate})$$

Figure 3.7: The basis of a production progress measurement

Moreover, the loading operations are mainly processed in the early phase of the assembly process. In latter phase, welding or finishing process is mainly processed. In other words, early phase of the assembly process can be measured acquiring the data from loading process, however it cannot represent the whole assembly process. In this regard, additional process information is needed to measure a reliable production progress. As additional process information is acquired, additional mediation between the field data and schedule is needed.

3.5 The ship block assembly monitoring system

To test and validate the production progress measurement method in Chapter 3.4, the ship block assembly monitoring system is developed. This system measures the production progress of the curved-block using the weight data acquired from the overhead crane. A testbed replicating an overhead crane workspace was used for data collection. To simulate the scoring method, virtual BoM and schedule was complied. Finally, monitoring program was created to simulate the production progress measurement method.

Figure 3.8: The ship block assembly monitoring system

3.5.1 Test environment

The best way to verify the production progress method is acquiring data from overhead crane in the real workspace. However, installing a new method to the workspace occurs idle time of the operation, and time and cost consumed as idle time continues. Using shipyard workplace, which has a huge opportunity cost, to verify the new method takes huge business risk. Moreover, program development schedule can be shortened by the immediate comparison between the operating status and the monitoring status. Due to the difficulty of immediate comparison, development can be delayed when a new method are verified using the shipyard from the early stage of development. To develop a program rapidly and to decrease the cost, overhead crane testbed is constructed displayed at Figure 3.7.

The specifications of this testbed are as follows.

- 2 linear actuators with each 800mm stoke for x-axis and y-axis transport
- A trolley with a stepping motor and gears for z-axis hoisting
- A load cell measuring up to 3kg and amplified with the fixed and the movable pulley (up to 12kg)
- Data acquired at 1ms sampling rate using RS232 communication

By using the control program, the testbed can carry the parts up to 12kg and weight them. Position of the trolley can be measured by acquiring the operation data of two linear actuators. Carried parts are loaded to the target using the stepping motor in the trolley. All the data are acquired and all the driving parts are controlled with RS232 communication.

Figure 3.9: Overhead crane testbed

3.5.2 Virtual BoM and operation schedule

To simulate the curved-block shop floor, operation scenario that reflects the field works was created. Two types of scenario are needed, one is a BoM in the database, and the other is an operation schedule in the field. The BoM has weight data identified with the part and each part is grouped with its target product ID. The operation schedule has the operation order and the weight of the part which is carried in that operation. Target block, x-axis, and y-axis columns guide the crane operator.

Table 3.5: Virtual BoM and Operation schedule for the simulation

Block ID	Part ID	Weight
B12	P1	7
B56	P2	7
B12	P3	30
B56	P4	11
B03	P5	23
B12	P6	21
B56	P7	21
B56	P8	25
B03	P9	2
B56	P10	7
B03	P11	21
B03	P12	13
B44	P13	27
B44	P14	2
	⋮	

(a) Virtual BoM

Order	Weight (t)	Target block	x-axis	y-axis
1	20.7	B56	35	15
2	22.1	B03	15	38
3	25.6	B12	11	9
4	2.4	B03	13	40
5	27.1	B56	39	14
6	17.9	B12	9	13
7	14.9	B03	18	34
8	6.8	B56	38	13
9	7.3	B56	35	18
10	8.2	B12	6	6
11	11.6	B56	34	13
12	20.1	B03	13	34
		⋮		

(b) Operation schedule

In the scenario, 4 blocks (B03, 12, 44, and 56) are scheduled in the BoM, and 12 parts are loaded to 3 blocks in the operation schedule. To verify the scoring method, the weight of the actual part was modified to the weight on database within 20 percent error range.

3.5.3 Simulation with monitoring program

Through the testbed, 12 transport and loading operations were simulated. For the weight data, actual weight is 10,000 times amplified and recorded because the weight limit of the testbed is 12kg. For example, 2.21kg part in testbed amplified and recorded as 22.1 tons in the database. Monitoring program simulated production progress measurement with the data acquired from the testbed in real-time.

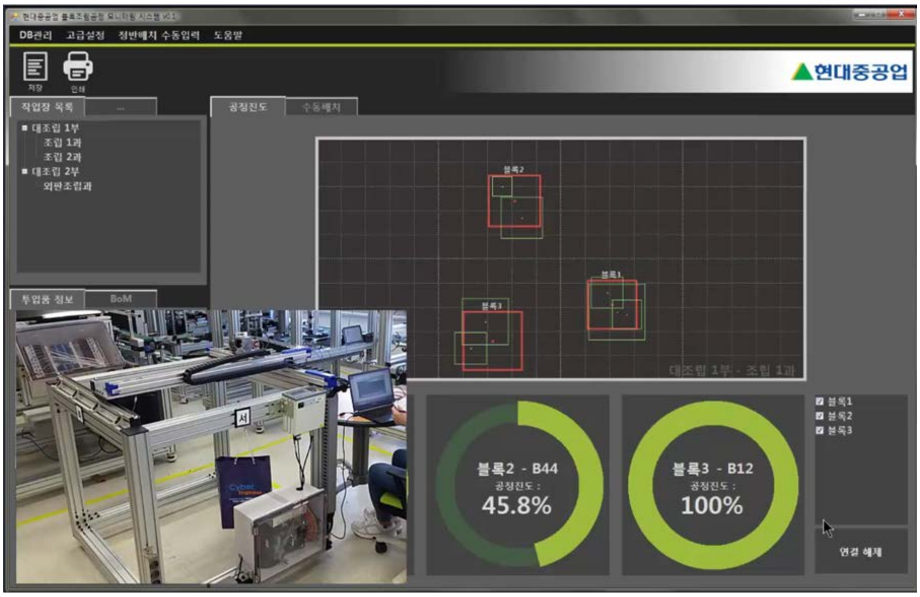


Figure 3.10: Production progress simulation with the monitoring program and the testbed

Each time the operation progresses, block ID estimation and progress measurement are performed and the result is logged in the database as displayed in Figure 3.11. Database logs basic information such as operation time and the target block, and also logs estimation score, production progress, and ID of the estimated block to 3rd rank.

투입 시간	투입 블록	1순위 블록	1순위 유사도	1순위 공정진도	2순위 블록	2순위 유사도	2순위 공정진도	3순위 블록	3순위 유사도	3순위 공정진도	사용자 정의
2016-05-18 21:39:11	1	A123	77.2	3.3	A214	77.2	2.2	A222	56.4	2.5	0
2016-05-18 21:39:28	2	A214	73.9	0.9	A184	73.9	5.2	null	0	0	0
2016-05-18 21:39:31	2	A184	60.4	11.7	A214	27.8	3	null	0	0	0
2016-05-18 21:39:35	3	A222	75.9	2.5	A184	74.1	10.4	A123	47.5	3.3	0
2016-05-18 21:39:40	1	A222	55.2	6.1	A214	51.5	4.7	A184	43.7	32.5	0
2016-05-18 21:39:45	1	A222	59.7	11.4	A214	55.3	9.7	A184	51.7	61	0
2016-05-18 21:39:50	3	A123	58	6.6	A222	52.8	6.1	A184	26.9	20.8	0
2016-05-18 21:40:21	1	A214	100	9.7		0	0		0	0	1
2016-05-18 21:39:56	1	A214	100	12.3		0	0		0	0	0
2016-05-18 21:40:29	4	A214	79.1	2.6	A222	65.1	3.6	A123	53.5	3.3	0
2016-05-18 21:40:35	4	A214	76.5	5.2	A222	71.4	7.2	A123	42.6	6.6	0
2016-05-18 21:40:41	2	A184	65.6	19.5	A123	17.5	7.3	A214	17.5	5.6	0
2016-05-18 21:40:46	4	A214	77.5	7.3	A222	70.1	9.7	A123	51.7	9.9	0
2016-05-18 21:41:07	3	A123	58.3	9.9	A222	54.6	9.7	A214	38.6	7.3	0
2016-05-18 21:41:12	1	A214	100	17.2		0	0		0	0	0
2016-05-18 21:41:16	3	A123	59.9	11.9	A222	36.4	14.7	A184	27.2	37.7	0
2016-05-18 21:41:20	4	A214	46.3	9.9	A222	45.1	14.7	A123	41.2	11.9	0
2016-05-18 21:41:25	2	A184	67.2	28.6	A123	27.1	10.6	A214	12.8	8.2	0
2016-05-18 21:41:31	1	A214	100	34.4		0	0		0	0	0
2016-05-18 21:41:36	4	A214	51	10.8	A222	33.6	19.7	A123	31	13.9	0

Figure 3.11: Log data of the block ID estimation and production progress measurement

Result of the simulation is displayed in Table 3.6 below. In the result, estimated ID which has the 100% progress data is originally scheduled block. It means that an estimated ID with a 100% progress result should have the highest estimation score to be the correct identification. Therefore, correct block identification is resulted in the field block 1 and 2. However, field block 3 estimates B12 which has 100% progress result in 2nd rank. This estimation error comes from the intended error in the weight distribution. B56, which has the highest score in field block 3 estimation, has similar part weights as B12.

Table 3.6: Result of the production progress measurement simulation

Target block	Estimated ID	Estimation score	Progress
Field Block 1	B56	76.5	100%
	B44	32.8	83.1%
Field Block 2	B03	63.5	100%
	B44	41.5	78.3%
	B56	25.4	90.1%
Field Block 3	B56	57.6	74.6%
	B12	49.1	100%
	B03	31.7	96.6%

Through this case, we can know that if the block is identified with only single information such as weight, it can give the invalid result from the errors in design and processing. In this regard, to decrease the errors from identification in production progress measurement, applying multiple information is needed such as position of the parts and product. The next chapter introduces 2 methods for manufacturing resource positioning which can be used to production progress measurement and also can be used for the other manufacturing process monitoring systems.

IV. Manufacturing Resource Positioning Methods

4.1 Problem statement

Position of the manufacturing resource is key information in manufacturing process monitoring. Like the flow-shop manufacturing, it is possible to monitor the production progress by defining the position of the product. From a maintenance point of view, positioning of the facilities or manufacturing tools are useful for inspection or scheduling. In addition, the positioning of individual parts can be used for flexible inventory management and rapid rescheduling. In the job-shop manufacturing, the position of the initial process mostly continues to the position of the finishing process. However, the curved-block case doesn't figure the initial position of the process and block can be transferred during in process according to a spatial schedule.

A simple solution for the block positioning is identifying the absolute position of the block itself. Applying a module such as RFID tags on the parts or products can provide the positional information to the monitoring system. However, as described in Chapter 3.3.2, many constraints of the curved-block assembly process hinder the application of a module or visual information gathering. Moreover, the ship-block constitutes the structure of the ship from the exterior to the interior as a key component. Therefore, when selecting a module installation method, additional operations for removing and inspections of a module cannot be ignored. In this regard, the relative positioning method using the overhead crane position is applied to the curved-block case.

To obtain the position of the overhead crane, the absolute positioning method should be applied to the overhead crane itself. We suggested several methods for the absolute positioning, and a method of acquiring the crane operational data by installing an encoder on the crane rail was selected. However, contrary to the overhead crane with rails, a new method is needed to obtain the position of the manufacturing resources which do not have a proper reference.

Numerous studies solve this problem with wireless communication technology (Chan 2010). However, most wireless technology is limited in its application in the curved-block workshop. The structure of both the workspace and the product is mostly metal, which can block the wireless signal. The size of the workspace is also another constraint. The size of the curved-block assembly workspace is at least 100 m and the maximum range of most commonly-used wireless technology does not fulfill this requirement. Constructing the mesh-network or applying long-range wireless communication technology can be the solution but these methods are difficult to manage and require significant cost.

We studied and tested a positioning method using acoustic signals to solve this problem. The sound source localization method can be a solution for the manufacturing resource positioning. However, if the identification is not preceded, the location information itself cannot be used. In this regard, we also studied and tested a data transfer method using an acoustic signal. We have discretized the acoustic signal to transfer the data.

4.2 Workspace estimation using the operation data of overhead cranes

Position of the product can be estimated with part positions, so applying the absolute positioning method to the overhead crane relatively can gather the product position. Furthermore, overhead crane is a facility which fixed in the workspace semi permanently. Therefore, it doesn't need additional operations such as removing. It also has advantage that multiple product positions can be estimated with a single positioning module. Several methods for obtaining the overhead crane position are introduced in the Chapter 4.2.1. The loading position of a single part can be obtained using position information of the crane, but this is not an exact position information of the product. Therefore, we developed a method to estimate the workspace of a product by using loading position of the parts and described it at chapter 4.2.2.

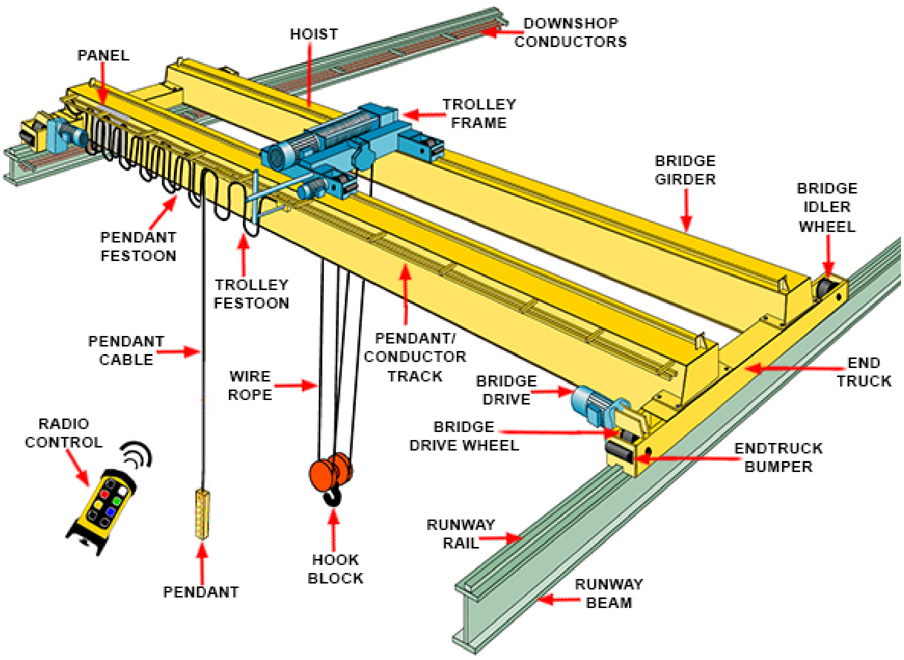


Figure 4.1: An overhead crane and its components illustration (Source: Munck Crane inc.)

4.2.1 Absolute positioning of the overhead crane

As displayed in the Figure 4.1, the overhead crane, also called bridge crane, is fixed on two parallel runway rails which is installed on the shop-floor structure. A trolley can move through the bridge girder in a direction perpendicular to two rails and it hoists and loads the parts on the product. In other words, a trolley moves on a workspace plane with two perpendicular linear motions.

The position of a trolley can be obtained in two ways, as referring or non-referring the manufacturing resources. Considering the linear movement of the trolley along the railway, linear distance measurement methods can be applied to the trolley positioning. On the other hand, by installing an absolute positioning module on the trolley, positioning of the trolley is possible without references. Based on these two ways, we studied several methods to obtain a position of the trolley and this is described at Table 4.1.

Trolley positioning referring the manufacturing resources

Linear motion in two direction of trolley is easy to apply position measurement method. In linear distance measurement, many studies already researched and many commercially available products are already on the market. Since directions of two linear motion are perpendicular, measured positions are easily converted in the rectangular coordinating system. In this aspect, we mainly studied about applying linear distance measurement method to the overhead crane.

Laser distance meter is used in wide range of industry fields. The advantage of this solution is that measurement device doesn't need to contact with the target product directly and it perform accurate distance measurement in real time. By applying two laser distance meters on the trolley can measure two perpendicular distances. However, when the obstacle blocks its line of sight, the distance to the obstacle is measured. Moreover, as maximum acquirable distance increases, the price becomes expensive to square.

Figure 4.2: Laser distance meter (Source: DIMETIX)

Table 4.1: Summary of trolley positioning methods

Type	Method	Description	Feature
Referring the manufacturing resources	Laser distance meter	· Laser distance meter measures distance between reflection plate and itself using a laser · Gap between transmitter and receiver is used to calculate distance	· Ensures high accuracy of distance measurement in real-time · Vulnerable to obstacles blocking line of sight
	Barcode distance meter	· The reader mounted on the trolley reads the barcode attached to the wall along the rail to measure the traveling distance	· When the barcode is damaged or contaminated, data loss occurs in the obtained driving information
	Inductive sensor	· Inductive sensor senses induction on the metal railway due to the traveling · Induction strength is converted to the speed data and data is converted to the distance again	· Even if the inductive sensors are dirty, the electromagnetic field is still in progress · Most inductive sensors are extremely robust
	Encoder	· Installing an encoder on wheel in the railway · The wheel speed is measured by the encoder and is used to estimate the travel distance	· Slip and friction of the wheel can make distance errors · Due to that distance errors are accumulated as the operation continues, periodic calibration is required
Non-referring the manufacturing resources	Wireless technology	· The transmitter mounted on the trolley generates a signal and receiver detect and identify it · Position of the trolley is measured using proper wireless positioning method	· In addition to positioning, information transmission is also possible · The high performance receiver is required when using transmission delay for the positioning
	Marker	· A camera records the visual information of the workspace · The markers attached on the trolley are recognized through image processing · Spatial information of the trolley is analyzed through workspace image	· When the marker is damaged or contaminated, it may not be recognized through image processing
	Light emitting diode	· Detection and positioning method is almost same with the marker method · Using light emitting diode, active visual data generation is possible	· The light can affect the work efficiency of the worker · Vulnerable to obstacles blocking line of sight
	Acoustic signal	· Acoustic signal is generated from the transmitter on the trolley · Multiple microphones records the acoustic signal · Recorded acoustic signal is processed and used to the positioning	· The acoustic signal can affect the work efficiency of the worker · It can be affected by the environmental noises · When discretization method is applied, information transmission is also possible

We have considered positioning methods by focusing on the characteristics of the railway which is fixed on the workspace and guides movement of the trolley. Using the characteristics that the shape of railway is not bent but straight, the position of trolley can be measured by attaching barcode to the railway. Barcode measurement sensor mounted on the trolley reads barcode attached in the railway to detect the position of the trolley and through this, intuitive coordinating is possible. To apply this method, protection and management of the barcode is highly important. When the barcode is damaged or contaminated, data loss occurs in the obtained driving information. However managing all barcode in the long railway needs much manpower and a high position of the railway installed is difficult to access.

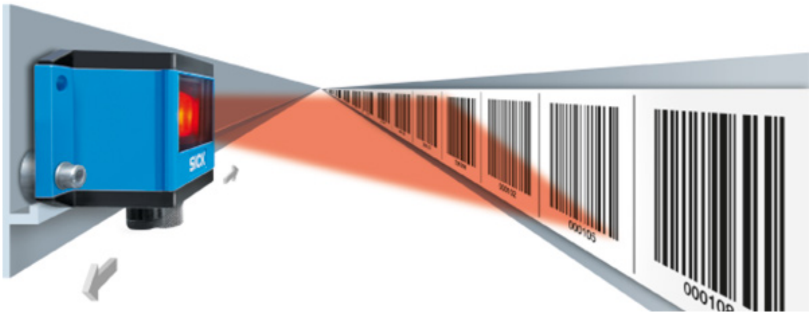
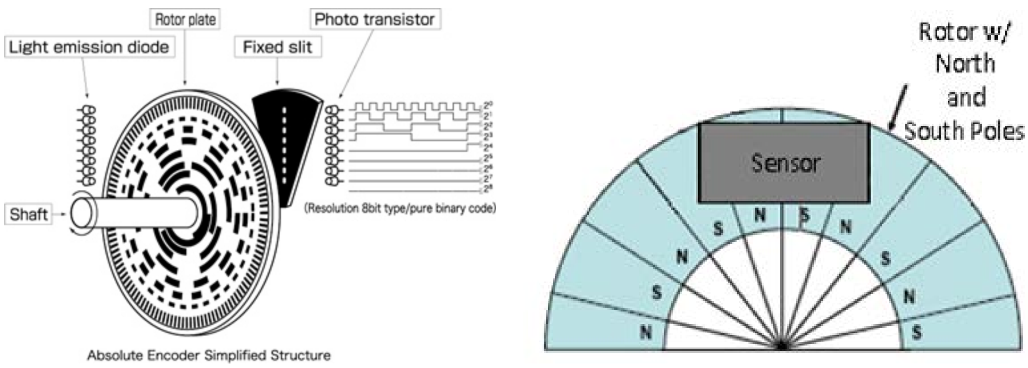


Figure 4.3: Linear barcode measurement sensor (Source: SICK)

Inductive sensor can be the solution for the pollution problem. Even if the inductive sensors are dirty, the electromagnetic field is still in progress. With this advantage, research has been studied on applying inductive sensors to the crane positioning (Legat et al. 2013). However, as strong to the pollution, most inductive sensors are extremely robust. Due to the structural nature of the inductive sensors using coils and electromagnetic induction, accurate data acquisition with it requires precise parts and also needs much cost.



(a) **(b)** .

Figure 4.4: Principle of Optical (a) and magnetic encoder (b) (Source: Anaheim automation)

By applying an encoder to the trolley wheel, the trolley speed in linear direction can be measured and this can be converted to the traveling distance. Applying encoder doesn't need additional installation on the railway and compared to other method, it guarantees high accuracy with low cost. In addition, different with laser distance meter case, it measure the speed of trolley which can be used in other monitoring methods such as operator safety monitoring system. However, slip and friction of the wheel can make distance errors and due to that distance errors are accumulated as the operation continues, periodic calibration is required.

Trolley positioning non-referring the manufacturing resources

If the absolute positioning method is directly applied to the trolley, positioning method doesn't need to refer other manufacturing resources. In many types of absolute positioning methods, we studied and excluded not proper methods for the curved-block shop-floor. For example, the GPS is a representative method in the absolute positioning. However, due to the reason that signal from the satellite is blocked by the ceiling, the GPS is not proper for the indoor workspace positioning.

Using wireless technology for the absolute positioning have been widely discussed and studied. However, there is financial constraint to apply those methods. Due to the huge scale of the shipbuilding industry, strong and long ranged wireless signal or fingerprinting method using mesh network is needed and applying those industrial wireless communication technologies need much cost. It is reasonable to introduce such technologies if increase of the productivity can be guaranteed, but it is difficult to apply the technology in the verification stage like this study. Moreover, several workspaces in the shipyard are bigger than the curved-block assembly workspace. Considering the further expansion of technology, even if the selected wireless communication technology satisfies the size of the curved-block shop floor, it is difficult to apply at the entire shipyard.

To reduce the cost for installation of the positioning module, a method using a visual marker can be applied. Visual marker is attached on the trolley and the camera records visual information of the workspace. Through the image processing, marker can be detected and spatial information of this can be analyzed (Yoshida and Tabata 2008). Since the position of the marker is same with the positon of the trolley, trolley position is detected in real-time. However, similar with the barcode method, it is vulnerable to pollution, so ongoing management for the marker is needed but due to the height of trolley it is difficult to access. Installing a light emitting diode is a solution that compensates for the drawbacks of marker. Unlike marker, visual information from the diode can generate a signal even in a polluted state. In addition, it can generate the signal such as color or flickering, so data transferring is possible with this solution. Both two methods have same characteristics that the camera cannot detect it when the line of sight is blocked. If a loading process is operated at this moment, the operation information is lost and this lost is fatal to process monitoring.

The acoustic signal positioning method doesn't need additional transmitter when using an original noise of the facility. This advantage makes management easy and the installation cost lower. If additional acoustic signal generator is installed at the target, data transmission is possible and it can be used for identification or fault diagnosis. In addition, if the non-audible frequency can be generated from the acoustic signal generator, the operator is not disturbed by the noise problem. A lot of things should be studied before applying these advantages to the overhead crane. For this reason, acoustic signal positioning method is not proper for the overhead crane positioning now. However, we focused on the advantage that it can be applied to other manufacturing resources, and this study is described in the Chapter 4.3.

In conclusion, among those trolley positioning methods, encoder, barcode distance meter, marker, and light emitting diode methods can measure the highly accurate distance or speed of trolley in low cost. Those 4 methods have different characteristics that are problematic when applied to the overhead crane. Barcode and marker methods need ongoing management to reduce the pollution problem. Light emitting diode method doesn't work properly when the line of sight is blocked. The problem in the encoder method can be solved with giving reference for the calibration. Finally, we selected an encoder method for the trolley positioning that applied a solution for the calibration problem.

4.2.2 Relative positioning of a product

Through the absolute position of the trolley, a loading position of the part is relatively measurable. Position of a curved block is also measurable using the characteristics of it. In the loading sequence of a curved block in figure 4.5, main panels are loaded at early in the process.

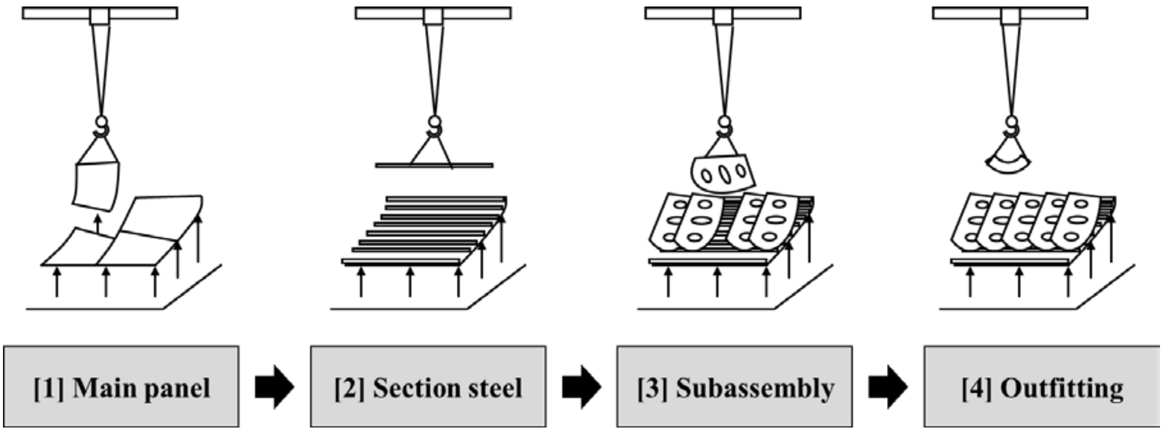


Figure 4.5: The loading sequence of a curved-block

Main panel forms the spatial basis of a curved-block. The moving plane of the trolley is parallel with the ground and in this plane, preformed spatial basis with main panel is rarely changed. At this point, coordinate information of the main panel can be used to form the workspace of a curved block. However, the coordinate information of the parts is recognized like the Figure 4.6 below, part grouping and product workspace estimation is needed.

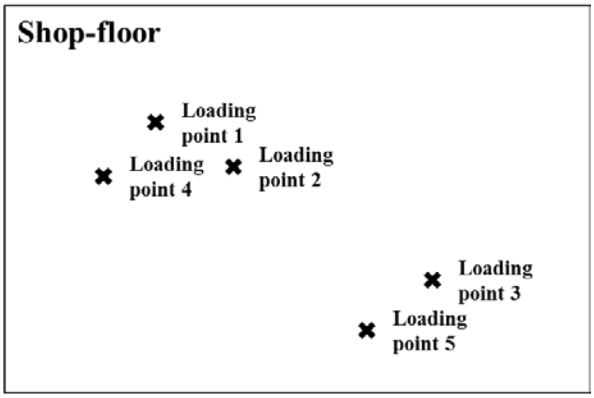


Figure 4.6: Coordinate information of loaded parts

Part grouping and product workspace estimation

We developed part grouping and product workspace estimation method using loading coordinate and weight of the parts. This method was developed under the following assumptions.

- Loading position is acquired as perpendicular x and y coordinate information
- Main panels are preloaded before the other parts
- Thicknesses and densities of the main panels are same
- After a panel is loaded, physically neighbor panel is loaded in the next order
- Shape of the blocks in top-view is fixed as a square
- Workspaces of the curved-blocks are spaced apart

Assuming that thicknesses and densities of the main panels are same, they have an area proportional to the weight. Final shape of the block in top-view is assumed as a square, and its length of one side equals root of the total weight. Part grouping and product workspace estimation are processed as the following figures.

If the part loaded in the empty workspace, it is regarded as a first main panel of a new block and it has a virtual area which is proportional to the weight. When a virtual area of newly loaded part overlaps with the virtual area of first main panel, those two panels are grouped and used to estimate the virtual area of product as displayed in the Figure 4.7 (a). The estimated virtual area of product has a weight of the sum of the weight of two main panels, and has an area proportional to the weight.

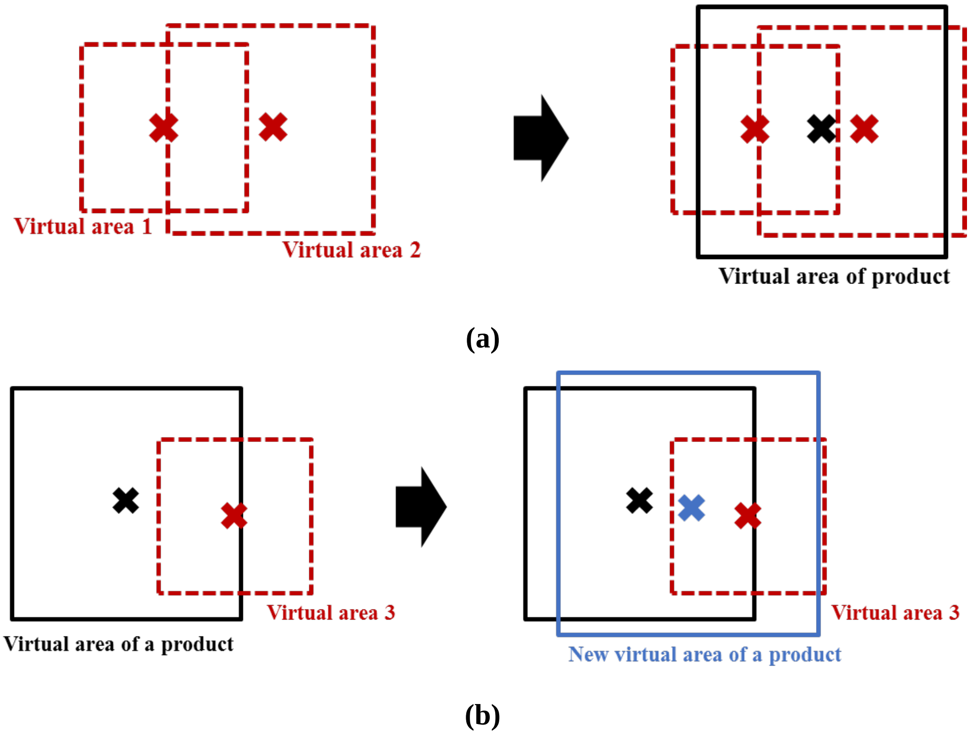


Figure 4.7: Principle of the workspace estimation

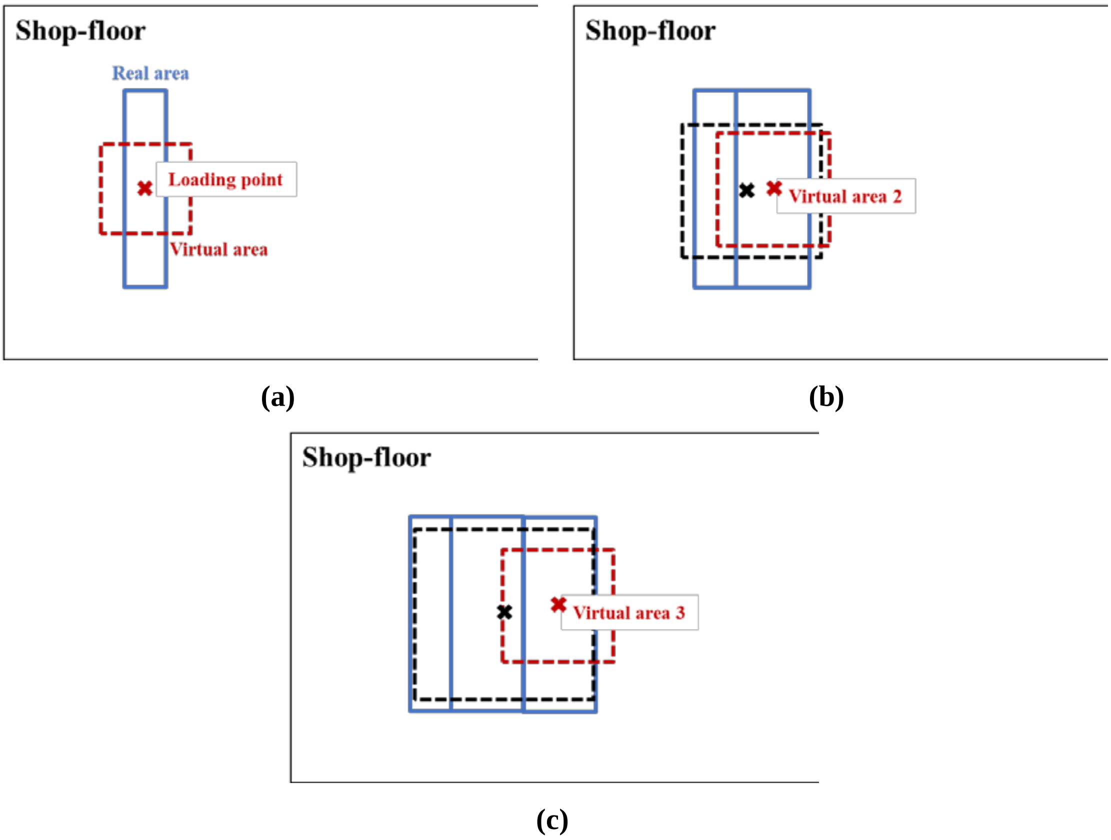
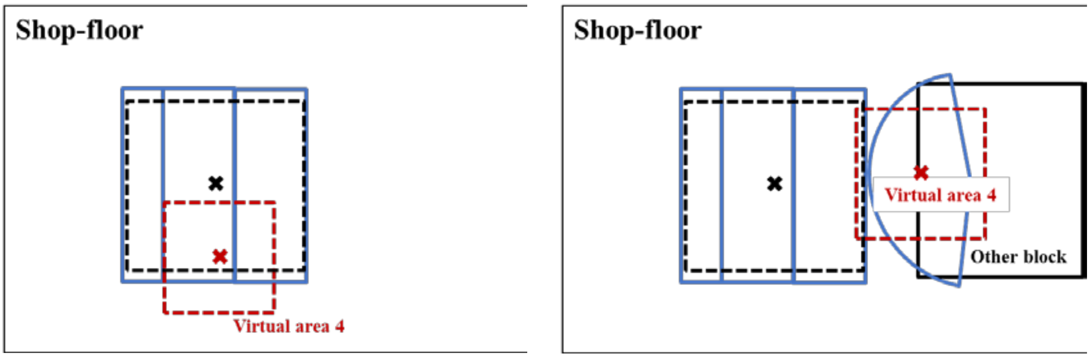


Figure 4.8: Example of the workspace estimation in a shop-floor

When a virtual area of newly loaded part overlaps with the virtual area of a product not the first main panel, newly loaded part is grouped with two prior panels and used to estimate the virtual area of product as displayed in the Figure 4.7 (b). The newly estimated virtual area of product has a weight of the sum of the weight of third main panel and prior two main panels, and has an area proportional to the weight.

Through this part grouping and estimation method, loaded main panels are grouped and used to estimate the workspace of the product. Even the shape of each main panel is not a square, final estimation of the product area is matched with a square and this process is exampled in the Figure 4.8. Furthermore, for the several cases, this method has the exceptional rules. First, after all main panel is loaded, part grouping is keep processing but a newly loaded part is no longer considered as a main panel. As exampled in the Figure 4.9 (a), workspace expansion also stops due to the weight summation stops. The point of the main panel loading stops is determined by the grouping method for the product identification described at the Chapter 3.4.2. The next exceptional case is displayed in the Figure 4.9 (b).



(a) **(b)**

Figure 4.9: Exceptional cases in the workspace estimation

A virtual area of newly loaded part overlapped with a virtual area of product. If the main panel loading is in progress, this newly loaded part should be considered as an additional main panel. However, if the area also overlaps with another block, the block containing the center of mass has priority for the grouping.

Workspace estimation in the ship block assembly monitoring system

The ship block assembly monitoring system described at the Chapter 3.5 is simulated with the part grouping and product workspace estimation method. We visualized the workspace estimation process in real-time and displayed it on the user interface like the Figure 4.10. Virtual areas of the products are displayed in red, and a newly loaded part is displayed in green.

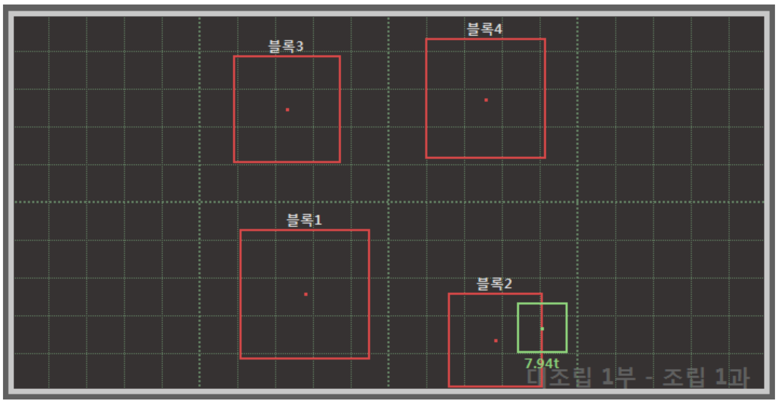


Figure 4.10: The visualized workspace estimation method on the user interface

Curved-block workspace can be estimated by applying encoder on the overhead crane and using workspace estimation method. Matching this estimated workspace with spatial schedule can be used to the production progress measurement and the operation guide. However, only with the weight data, this method can be applied when a shape of the product in top view is square. Furthermore, this method is dependent on the process sequence so change of the sequence interrupts the grouping and the workspace area estimation such as loading outfitting before the main panel. To solve these problems and improve the method, additional information is needed as in case of production progress measurement.

4.3 Acoustic signal positioning

As described in the Chapter 4.2.1, absolute positioning is possible using acoustic signal. In overhead crane case, this method has several constraints to adopt in the overhead crane positioning or curved-block positioning. First, noise from the acoustic signal affects the work efficiency of the operators. Using non-audible frequency can be a simple solution for this but the high price of equipment that can generate and acquiring such signals. Second, characteristics of the acoustic signal is sensitive to the surrounding environment. As temperature and humidity changes of atmosphere, speed of the sound changes (Nelson and Stoddard 1998). This change affects to the TDOA estimation described in the Chapter 4.3.1 but speed estimation in those environment can be easily calibrated using relative equations. However, when the speed of sound changes due to the medium changes (Askariyan et al. 1979), it is hard to define all of this mediums. In addition, reflection and refraction of the sound affect to the speed estimation.

Despite these limitations, sound is one of the most important cues for locating facilities with a noise. Sound waves travel in all directions and can be detected at long distances from the sound source, and beyond line of sight. In dark, dust, smoke, or otherwise cluttered environments, acoustic signals are far more reliable than visual cues (Basiri et al. 2012). If a facility has its unique sound, identification through acoustic signal is possible. However, multiple facilities of the same kind are operated in the same workplace, so it is difficult to identify the facility by sound classification alone. In this regard, we developed a method for the positioning and data transferring with one cycle of the acoustic signal

4.3.1 TDOA estimation

TDOA is one of the lateration techniques in the triangulations. The idea of TDOA is to determine the relative position of the mobile transmitter by examining the difference in time at which the signal arrives at multiple measuring units, rather than the absolute arrival time of TOA (Liu et al. 2007). This concept is displayed at the Figure 4.11.

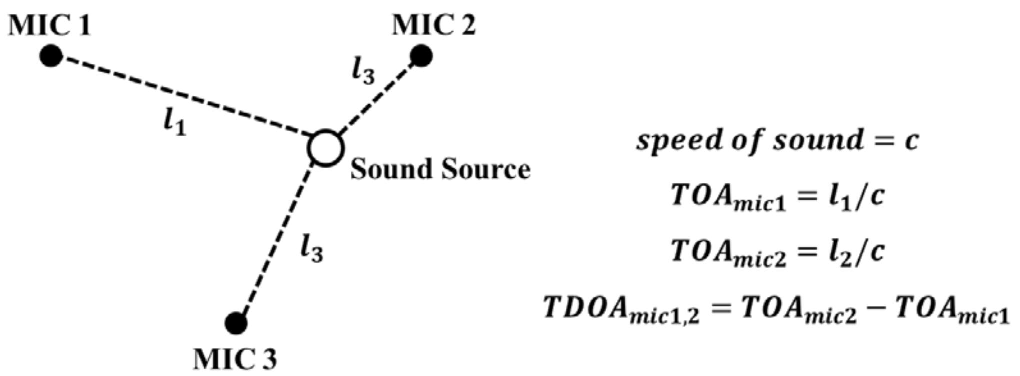


Figure 4.11: Basic concept of TDOA

Time difference estimation

To estimate the time difference, we segmented acoustic signal in window with N samples. A time difference cannot exceed the time that distance between two microphones divided by the speed of sound. Therefore, time of a window, the product of N samples and sampling rate, should not be less than the maximum time. From two microphones, two windows of acoustic signal can be acquired at the same time. Through determination of the gap between two windows, time gap can be estimated. The most common coherence measure is a simple cross-correlation between two windows, as expressed by the equation below (Valin et al. 2003).

$$\boldsymbol{R_{ij}(\tau)} = \sum_{n=0}^{N-1} \boldsymbol{x_i[n]x_i[n-\tau]}$$

Where $x_i[n]$ is the n^{th} sample in the signal from microphone i and τ is the correlation lag in samples. The cross correlation result $R_{ij}(\tau)$ has maximum value at correlation lag τ is equal offset of two signals. Product of maximum τ and sampling rate is the TDOA between two microphones. Through the basic cross correlation, time difference between two microphones can be estimated, and complexity of this method is $O(N^2)$ by the Big-O notation (Bernal and Trujillo). However, an approximation of correlation lag can be computed in the frequency domain by computing the inverse Fourier transform of the cross-spectrum. This method reduces the complexity to $O(N\log_2 N)$ and is described at the equation below.

$$\boldsymbol{R_{ij}(\tau) \approx \sum_{n=0}^{N-1} X_i(k) X_j(k)^* \, e^{t2\pi k\tau/N}}$$

However, through this method, various peaks are occurred and the maximum value is all we need in TDOA case. To give the weight to the values around maximum value, PHAT (phase transform) filter is adopted. With this filter, whitened cross correlation also named "GCC-PHAT (General Cross Correlation with phase transform filter)" method and it described in the equation below (Omologo and Svaizer 1994) (Velasco et al. 2015).

$$\boldsymbol{R_{ij}(\tau) \approx \sum_{n=0}^{N-1} \frac{X_i(k) X_j(k)^*}{|X_i(k)|\left|X_j(k)\right|} e^{t2\pi k\tau/N}}$$

Target direction estimation

Using acquired time difference, the sound source must lie on a hyperboloid with a constant range difference between the two microphones. As displayed in the Figure 4.12, a location of sound source in 2-dimention can be estimated from the intersection of two hyperboloids which are generated with at least 3 microphones.

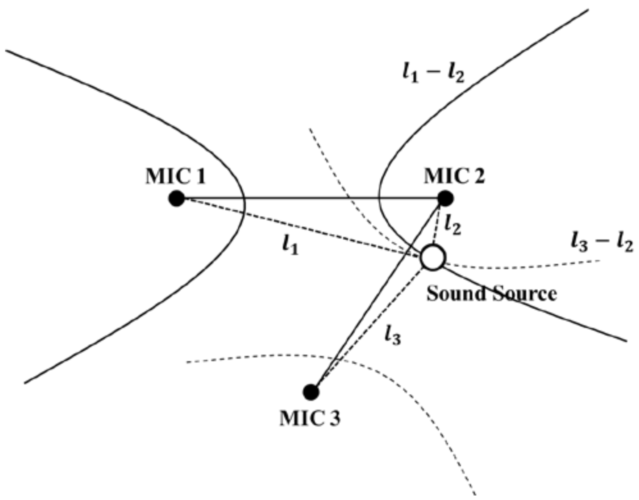


Figure 4.12: TODA estimation using hyperboloid

With this hyperboloid method, accurate position estimation is possible when a sound source is located around the microphones. However, as the distance between a sound source and the group of microphone increases, the error increases. The microphones can be installed widely in the case of small size workplace, but in the case of large size, there are some limitations. To install multiple microphones in the large space, two methods are possible, using long wire or installing multiple DAQ (data acquisition) modules. Using multiple DAQ has synchronization problem. To estimate TDOA, all DAQ should synchronize their system time and this need additional cost. Using long wire to connect each microphones and DAQ has risk of the disconnection and the signal distortion.

To solve this problem, a geometrical calculation can be a solution. Assuming that all microphones recognize acoustic signal from the same direction due to the long distance to the sound source. Then directional and angular relations between two microphones and the sound direction can be illustrated as the Figure 4.13.

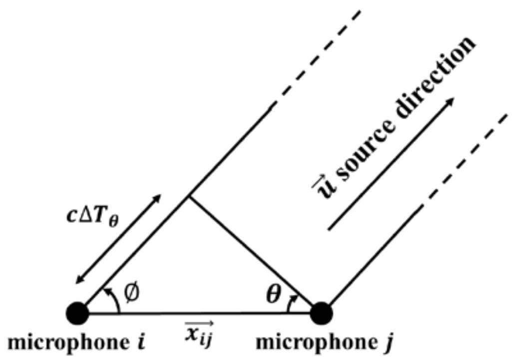


Figure 4.13: Geometrical sound direction estimation

In the illustration, c is a speed of sound, $\vec{u}$ is a unit vector pointing the sound source, ΔT_θ is the time difference between two microphones, and $\overrightarrow{x_{ij}}$ is a vector between two microphones. Using the cosine law, we can state cosØ as below

$$\cos\emptyset = \frac{\vec{u}\cdot\overrightarrow{x_{ij}}}{\|\vec{u}\|\|\overrightarrow{x_{ij}}\|} = \frac{\vec{u}\cdot\overrightarrow{x_{ij}}}{\|\overrightarrow{x_{ij}}\|}$$

and also

$$\cos\emptyset = \sin\theta = \frac{c\Delta T_{ij}}{\|\overrightarrow{x_{ij}}\|}$$

When combining those two equation,

$$\vec{u}\cdot\overrightarrow{x_{ij}} = c\Delta T_{ij}$$

To estimate unit vector pointing the sound source in 3D environment, the vector $\vec{u}$ and $\overrightarrow{x_{ij}}$ are defined as

$$\vec{u} = (u_x, u_y, u_z)$$
$$\overrightarrow{x_{ij}} = (m_{ijx}, m_{ijy}, m_{ijz})$$

From those equation, a linear system of N equations can be obtained when N different microphone-pairs, which are referring microphone 1 as a standard, are used

$$\mathrm{A} \cdot \mathrm{u} = \mathrm{b}$$

$$\mathrm{A} = \begin{bmatrix} m_{12x} & m_{12y} & m_{12z} \\ m_{13x} & m_{13y} & m_{13z} \\ \vdots & \vdots & \vdots \\ m_{1Nx} & m_{1Ny} & m_{1Nz} \end{bmatrix} \quad u = \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix} \quad b = \begin{bmatrix} c\tau_{12} \\ c\tau_{13} \\ \vdots \\ c\tau_{1N} \end{bmatrix}$$

A value for u can be estimated using the linear least square method (Lawson and Hanson 1995)

$$u_{ls} = (A^T A)^{-1} A^T b$$

To estimate a unit vector, matrix A should have 3rows at least. In other word, to estimate the direction of the sound source in 3 dimensional space, at least 4 microphones are needed. Expansion of the unit vector points the position of acoustic signal. In the case of overhead crane that moves in the 2 dimensional plane, contact point of the direction and the plane makes mapping of the overhead crane.

4.3.2 Data transfer using sound source discretization

As described in the previous chapter, product identification is a prerequisite of the progress monitoring system. Only with direction of the sound source, it has limit to be used for the production progress measurement. Giving unique frequency to each part or product can used for the identification. For example, part number 2645 generates 2645Hz acoustic signal, then it can be easily analyzed using Fourier transformation. However, if the unique frequency is not adjustable, additional manpower for maintenance is needed. For the frequency adjustable module, additional electric circuit is needed and applying a circuit only for identification is a waste of resource.

To solve this, we discretized the signal for the binary data transferring. Binary data can give the ID information and also additional information such as state of a part. Discretized signal is generated in a predefined frequency. Acoustic signal in predefined frequency means 1 (true) and 0 (false) at silent. When true values occur consecutively, a short silent interval is inserted between the signals for discrimination. We used 8-bit binary data for the signal transferring as displayed in the Figure 4.14.

After acoustic signal is generated, we acquired and processed for the analysis. First, acoustic signal is acquired at the microphone as displayed in the Figure 4.15. This signal is acquired in 4 microphones but for the data transferring, only one microphone is used. Acquired signal is processed with discrete

Fourier transform and bandwidth filter for discrimination. Summation of the DFT result shows power spectrum as displayed in the Figure 4.16 upper. Peak point of the power spectrum that reaches over predefined threshold shows time of the true value occurs. Data transferring and analyzing is possible with acoustic signal discretization and this can be used for the product identification and production progress measurement.

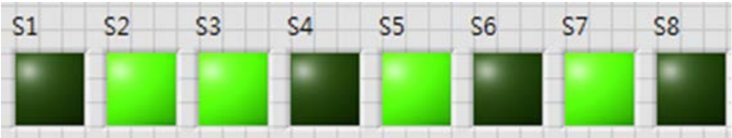


Figure 4.14: Discretized signal generation in predefined frequency

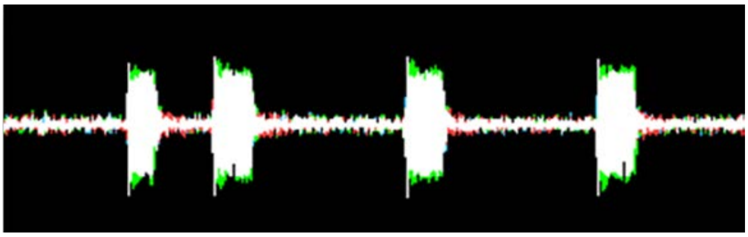


Figure 4.15: Data acquisition using a microphone

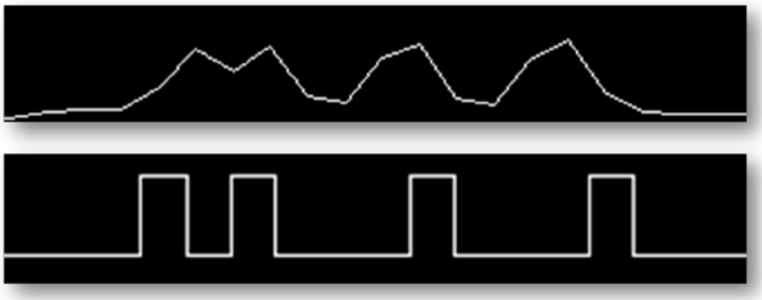


Figure 4.16: Signal Processing with power spectrum threshold

4.3.3 Positioning and data transfer using microphone array

Using acoustic signal in constant frequency is not proper to calculate correlation lag. Constant frequency shows constant correlation in every window. Sound source localization using TDOA only with the discretized acoustic signal can give unreliable result. Therefore, positioning and identification cannot be processed at a time through the acoustic signal discretization. Moreover, repetitive transmission is required for reliable transferring of data, so additional protocols are needed to define the start and end of data with signal discretization only.

We solved these problem by developing 2-phase acoustic signal method as displayed in the Figure 4.17. At phase 1, plosive sound is generated using frequency transition. From low to high frequency, plosive sound is generated. Through this signal, correlation lags can be calculated between each microphone. This signal is also used to define the start and end of the data transferring phase as a protocol. At phase 2, discretized signal is generated for the data transferring. Sinusoid in constant frequency transfers data in binary code. Through this 2-phase acoustic signal method, both positioning and data transferring can be processed at a time with one cycle of the signal.

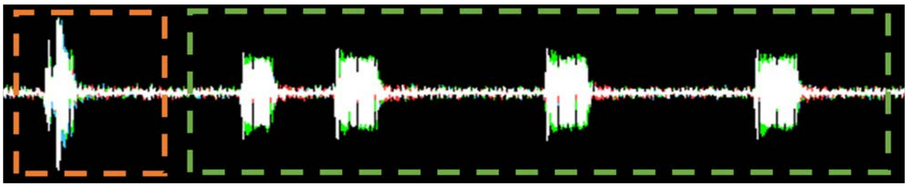


Figure 4.17: 2-phase acoustic signal

To experiment this method, we made tetrahedron array of 4 microphones as displayed at the Figure 4.18. The length of one side is 300mm. Microphone in front of the tetrahedron is used as a reference. 3 correlation lags are calculated from this microphone and other three. Discretized signal is also acquired from the reference microphone. Through the experiment, positioning and data transferring is reliably processed in 5m range. When the sound source goes far from the microphone, positioning results are susceptible to noise at phase 1. Moreover, as sound source goes far from the microphone, additional calibration for the power spectrum threshold is needed in phase 2.

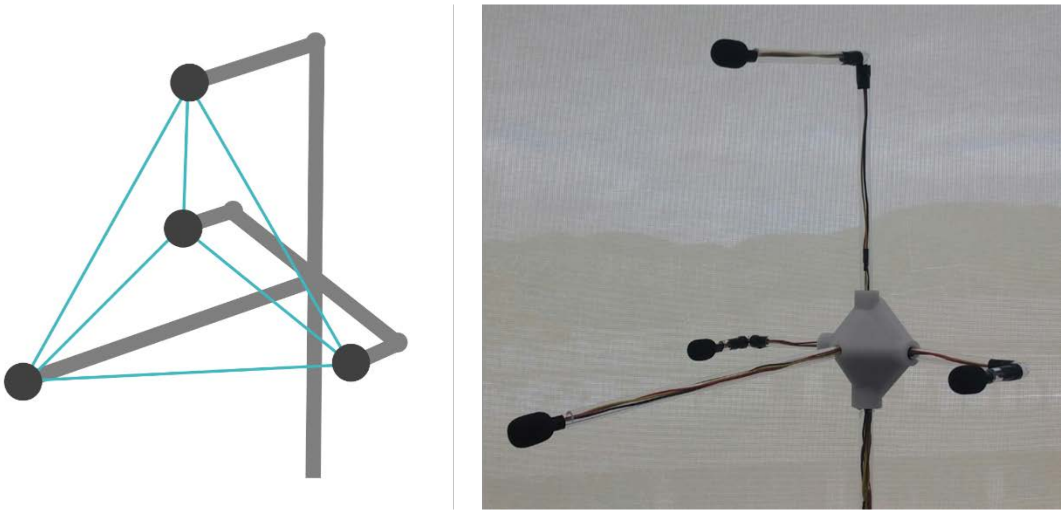


Figure 4.18: A regular tetrahedron array of 4 microphones concept (left) and real model (right)

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V. Conclusion and Future research

A method for the curved-block assembly process monitoring system was proposed. In particular, the production progress of the curved-block is monitored through the overhead crane, and the workspace is estimated through the crane positioning, while the positioning and data transfer is tested through the acoustic signal.

The proposed production progress measurement method can estimate the loading progress of a product based on the weight of its parts. Using only the weight data acquired from an overhead crane, products are identified with the grouping and scoring method. Based on the score, the weight information of the product schedule, which has the highest score, is compared with the loaded parts in the field. By comparing those two information, the loading progress is estimated. However, the simulation results show a weakness of this method. The ID estimation, using only the single data, is dependent on the error of the single data per se.

The proposed manufacturing resource positioning method can estimate the workspace of a product. Absolute positioning of the overhead crane is used to measure the loading position of the part. Through the grouping of the part using the crane operation and weight data, the workspace of the product is estimated. However, this method needs several assumptions of the parts and products to estimate the accurate position. To solve this limitation and expand the applicable range, the positioning method using an acoustic signal is also proposed. Through the sound source positioning method, the location of the sound source is estimated. In addition, data transfer is tested through the acoustic signal discretization. However, it also has several issues when directly applied to this field, such as absence of the distance and the noise problem.

The direction of future research can be summarized as follows: first, multiple data acquisition and applications are needed for the production progress measurement. For example, if welding operation data is acquired, the estimated progress of the weight can be verified and modified through the welding operation. Second, an extra microphone array should be added for the distance measure and sound source mapping. Finally, the acoustic signal at a non-audible frequency should be applied to improve the sound source localization performance.

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유니스트에서 보낸 시간들이 행복했습니다.