# Development and Application of a Systematic Innovation Procedure for Construction Technology

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## *Abstract*

Technology innovation has been recognized as a main driver for the advancement of construction industry. Due to the lack of systematic innovation procedure, the advancement of construction technologies has been slow compared with the other industries, e.g., ICT and Biotech Engineering. This paper proposed a Systematic Technology Innovation Process (STIP) for innovation of construction technologies. The STIP method integrates several techniques adopted for product research and development in other fast innovating industries including patent mapping, root cause analysis, TRIZ, function modeling, simplify design, etc. Details of the proposed STIP method are revisited. The pit-hole repairing technology for road maintenance work is selected for case study. Step-by-step application of the STIP method to the selected construction technology is demonstrated. Deliverables obtained from each step of the STIP is reviewed and evaluated via a technology stage gate (TSG) process, which is commonly adopted in high-tech manufacturing industry. Finally, an innovative design of new pit-hole repairing technology is developed. Evaluation of the innovative technology is also conducted to ensure its feasibility.

***Keywords***: Technology innovation, patent analysis, TRIZ, process model

## 1. Introduction

Construction technology was defined as "the combination of construction methods, construction resources, work tasks, and project influences that define the manner of performing a construction operation" [1] to "accomplish a desired aim necessary for human sustenance and comfort" [2]. Robert Harris pointed out that "…there is more to the construction process than just management…there is more to the construction process than just structural design or geotechnical evaluation…[We need] to create better methods for construction…"[3]. Technology innovation can result in revolutionary advancement in construction practice that traditional management techniques and other skills cannot achieve. Therefore, it becomes the critical component for a company's long-term competitive strategy [4].

However, innovation of construction technologies has been slow compared with other areas in Civil Engineering and other industries, e.g., Information and Communication Technology (ICT), Bio Genetic Technology, Nano Materials, etc. (Nam and Tatum, 1989). One of the critical reasons and maybe the most important one is the lack of a systematic approach for fast innovation [5]. As pointed out by Daniel Halpin in his speech of the Seventh Peurifoy Construction Research Award: "…we need a common framework—a common language" [6]. A Systematic Technology Innovation Process (STIP) is proposed to respond the appeals posed by previous researchers. The goal of STIP was to provide a common framework for fast innovation of construction technologies based on modern product innovation methods adopted in other highly innovative industries. In this paper, the STIP method is applied to innovate pit-hole repairing technology for road maintenance work.

The rest of the paper is presented in the following manner: the previous researches on construction technology innovation are reviewed in the second section; the Systematic Technology Innovation Process (STIP) for fast innovation is proposed and described in details; a case study on the application of STIP to innovate a pit-hole repairing technology for road maintenance work is described in the fourth section; finally, conclusions are drawn and future researches are suggested for interested researchers.

## 2. Construction Technology Innovation

Innovation of construction technologies has resulted in dramatic revolutions in construction practice. For example, the introduction of Portland cement in 1824 has brought up thousands of new construction technologies and equipment that completely change the way of construction engineering; furthermore, in the first quarter of the 20th century, the steel structural technology was invented and introduced to construction industry, which triggered a second revolution of construction technologies. During the late 1970's, construction industry suffered in low productivity, hence inspired the next generation of construction innovation. Issues such as constructability (O'Connor and Miller, 1994), prefabrication, modularization (Tatum et al., 1986), and automation (Sarah, 1997) have drawn numerous researchers to devote in the innovation of construction and management processes.

In spite of tremendous efforts spent, innovation in construction industry has been relatively slow. Lack of a common framework, as pointed out by Halpin, may contribute significantly to this lag. Previous researchers have exploited many approaches for organization process innovation [1], technology evaluation [7], and advanced technology repositories [8]. However, few of these efforts target directly to design of new technologies. Halpin proposed a CYCLONE model for analysis of construction processes [9]. Many efforts on construction process simulation followed him, e.g., COOPS [10] and STROBOSCOPE [11]. Most of the functionalities of process simulation techniques are still limited to the modeling of existing processes, rather than the invention of new technologies.

Just recently, a new area of construction innovation has been developing on patent analysis (PA) [12][13] and the Theory of Innovative Problem Solving (TRIZ) [14][15][16]. The former innovates the target technology based on existing technologies of the other areas, which are stored in public patent databases; the latter applies a systematic procedure to identify engineering potentially improvable attributes with tools provided with TRIZ [17].

Unlike the simulation approach to innovate the existing construction processes, PA- or TRIZ-based technology innovations seek a different dimension of technology improvement. The former belongs to "incremental innovation", and the latter belongs to "system innovation" or "radical innovation" according to the classification of Sarah Slaughter [4]. The "system" or "radical" innovations usually involve tremendous amount of information and knowledge and need to be performed with assistance of computer aided tools [18]. Such tools are incorporated into a systematic technology innovation process called STIP, which will be described in the next section.

## 3. Proposed Systematic Technology Innovation Process (STIP)

The objective of STIP method is to achieve a fast innovation of construction technologies by integrating three modern techniques: (1) a product research and development procedure called Research and Development Project Management (R&D PM); (2) an inventive problem-solving method namely TRIZ; and (3) a computer aided innovation tool called Goldfire Innovator™. The STIP procedure consists of eight steps described as follows.

### *3.1 Root Cause Analysis (RCA)*

The RCA step analyzes the potential opportunities for improvement with the identified technology problem. This step is associated with the Opportunity Analysis stage of the R&D PM Process. Two CAI tools are employed to perform RCA: the RCA module and knowledge database provided by Goldfire Innovator™.

### *3.2 Target Technology*

The Target Technology step searches the patent database for the root causes determined in the last step. This step is associated with the Concept Definition stage of the R&D PM Process. The patent databases and patent search tools can be employed to identify the target technology.

### *3.3 Function Modelling*

The Function Modelling step constructs the function model (FM) of the target technology identified in the last step. This step is associated with the Conceptual Design stage of the R&D PM Process. The Function Modelling module of Goldfire Innovator™ can be employed to construct the FM of the target technology.

### *3.4 FM Modification*

The FM Modification step modifies the FM of the target technology obtained in the last step. Principles of TRIZ, CT, value engineering, or simplify design can be adopted for this end. This step is associated with the System Analysis and Basic Design stage of the R&D PM Process. The Simplify Design module of Goldfire Innovator™ or any other innovative solution generator (ISG) commercial software can be employed to construct the FM for the target technology. The result of FM Modification is an "innovated alternative" that improve the problem of the target technology.

### *3.5 Alternative Evaluation*

The Alternative Evaluation step evaluates the modified FM of an innovated alternative generated in the last step. The result of evaluation can be "approval" or "rejection". If the alternative is approved, the STIP proceeds to next step—Method Design; on the contrast, should the technology alternative be rejected, the process goes back to FM Modification to generate a new alternative. This step is similar to the technology stage gate (TSG) of the R&D PM Process [19], which provides the innovator a quality control function of product development.

### *3.6 Method Design*

The Method Design step generates feasible solutions for an approved FM of an innovated alternative; that is, suggests a combination of resources (e.g., devices, materials, equipment, and human resources) and process to implement the innovated technology. This step is associated with the Product Design stage of the R&D PM Process. The knowledge database provided by Goldfire Innovator™ can help the innovator in generating technology solutions. Other approaches for Method Design include brain storming, focus group, and expert interviews when the CAI is not available [19].

### *3.7 Prototyping*

The Prototyping step implements the innovated technology generated in the last step with the available resources and methods. The implementation is experimental rather than formal. The objective is to test the feasibility of producing physical and practical methods that can be experimented or tested in the next step. This step is associated with the Prototyping stage of the R&D PM Process.

### *3.8 Experiment and Testing*

The last step of STIP method is Experiment and Testing. In this step, the prototyped technology is tested with real world scenarios to verify its feasibility and applicability. Design of Experiment (DOE) can be adopted to plan the experiments for testing. Modifications and adjustments may be made to the previous steps (Method Design and Prototyping) if the experiment results show potential problems of the prototype technology.

## 4. Case study

The STIP method was successfully applied to improve a product (or device) type technology, e.g., reinforced concrete (RC) building pipeline leakage repairing technology [5]; however, it has never been applied to innovate a process type construction method. There are two objectives for this case study: first, to investigate the applicability and feasibility of STIP fast innovation method for process type technologies; second, to develop an innovative design for the pit-hole repairing technology for road maintenance work.

### *4.1 Scope of Case Study*

The case study was conducted in Taiwan to innovate the pit-hole maintenance and repairing technology for asphalt concrete (AC) road pavement. Due to the limitation of time, the scope of patent search was limited to USTPO [20].

### *4.2 Application of STIP Method*

(1) Root Cause Analysis (RCA)

The two critical requirements of the existing AC road repairing technology are the confined working zone (to maintain the operation of the road) and limited time available for performing the work. The focus of this study is put on the latter, fast repair requirement, which is identified to be more desirable for practical construction than the former by interviews with the domain experts. An RCA diagram is drawn, as shown in Figure 2, to illustrate the root causes leading to slow repairing works of AC pavement. In Figure 2, there are two roots causing slow road pavement repairing works: (1) inaccurate material supply—this causes adjustment and reapplying required during the repairing work, and those works prolong the repairing time; (2) insufficient strength development of AC material—this cause the extra time required after repairing work is done. Both of the above causes are responsible for the slow repairing work. Noted that the wet conditions in rainy days can also cause delay of road repairs. However, according to the specifications road works in Taiwan, it is not allowed to perform road pavement work under rains. As a result, the wet condition is not considered in the RCA.

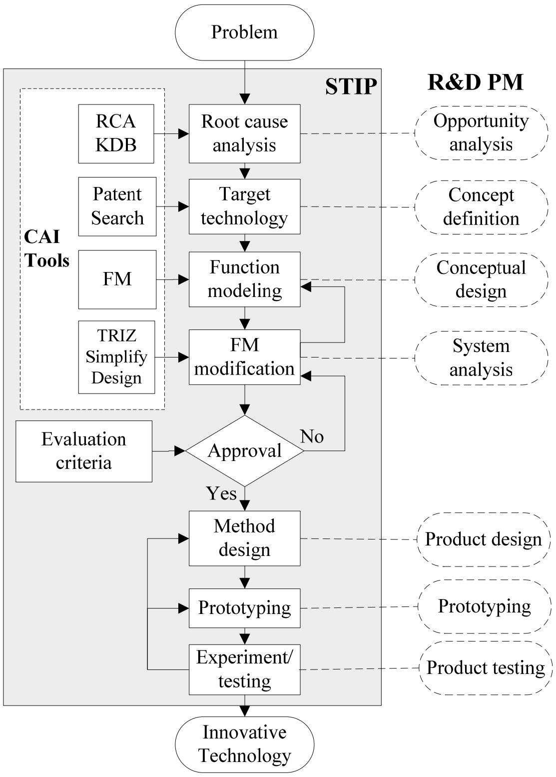

Figure 1 STIP procedure

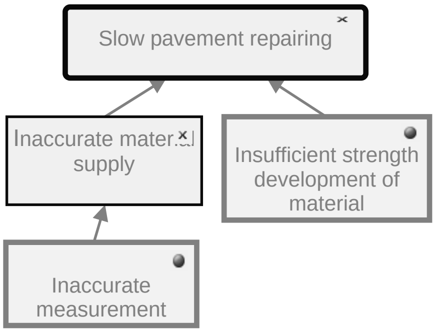

Figure 2 RCA diagram for slow road repair works

Further investigating the cause of “inaccurate material supply”, it is found the inaccurate measurement of the material required is the root. Therefore, providing an “accurate measuring method” is the key to solve the “inaccurate material supply” problem. Similarly, providing a high early-strength AC material can solve the “insufficient strength development of material” problem.

The root causes identified by RCA method is used in the next step to search for candidate technologies.

(2) Target Technology and Patent Search

In this step, the patent databases are searched to find out the most appropriate technology that can be considered as the "target technology" for innovation. At first, patent maps are developed to visualize the status of the technological competitiveness in the considered technology domain.

Table 1 shows the search criteria for pavement repairing technologies used in this research to find out the relevant patents in USPTO. The International Patent Classification code (IPC) was adopted in the search. In Table 1, it is noticed that the IPC class: "E01C 23/00" (build, repair, fix, rehabilitate, or demolition of road or similar facilities) was found to be most relevant to the problem domain of the case study.

Table 1 Search criteria for pavement repairing technologies

| |
|---|
| (((TTL/repair OR ABST/repair OR ACLM/repair OR TTL/rehabilitate OR ABST/rehabilitate OR ACLM/rehabilitate OR TTL/mend OR ABST/mend OR ACLM/mend OR TTL/renew OR ABST/renew OR ACLM/renew)) OR ((ABST/pavement OR TTL/pavement OR ACLM/pavement OR TTL/way OR ABST/way OR ACLM/way OR TTL/road OR ABST/road OR ACLM/road))) AND (ICL/E01C23/00 OR ICL/E01C23/06):579 patents |
| E01C 23/00: build, repair, fix, rehablitate, or demolition of road or similar facilities. |

The search results are used to constructed patent maps (Yu et al., 2006) so that the competitors of the technology domain can be identified. Some of the patent maps are shown in Figure 3 to 5. The analysis results showed that the patent activity chart shows that road repairing technology is declining in the past five years and top three competitors in the technology domain are Eigenmann, Wirtgen, and CMI.

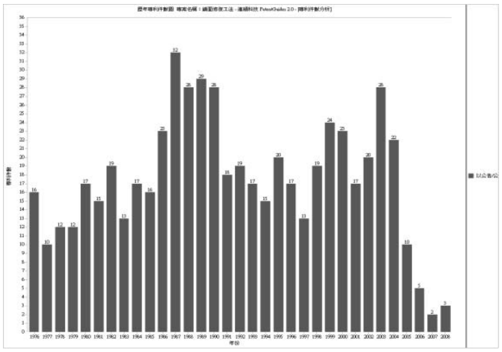

Figure 3 Patent quantity comparison chart (Publication date)

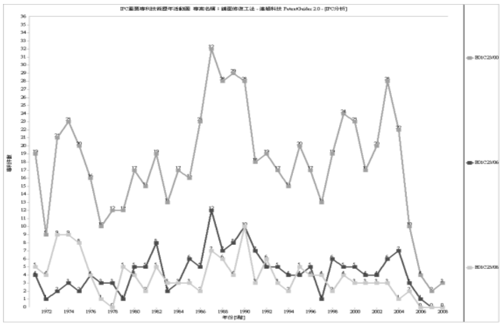

Figure 4 IPC patent activities (TOP 3)

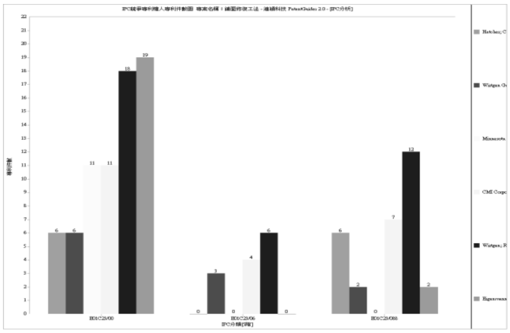

Figure 5 IPC patents of competitor companies (IPC TOP3, Asignee TOP 6)

By reviewing the most relevant patents, the “US4084915: Method for reconditioning and resurfacing pavement” is selected as the target technology for innovation. Since the patent documentation published by USTPO does not describe the construction process of the target technology, domain experts are consulted and a Hot-mixed AC Refilling Method for AC pavement repairing is conceived to be most relevant to the target technology. The construction process is described as follows.

Material Requirements: refilling material should be hot-mixed dense graded AC with aggregate of maximum diameter 13 mm.

Construction method:

- Clean deteriorate material of the damaged portion and the surrounding area of pit-hole with mechanical cutter. The cutting face should be plane.
- Remove the loose aggregate and sundries.
- Coating the cutting surface with a cohesive layer (the cement asphalt mortar can be used).
- Fill in hot-mixed AC material to the pit-hole. Flat the material to out stand the repair surface for 2~3 mm.
- Compact the repair surface with roller.
- Curing until the development strength of the material is sufficient for operation.

(3) Function Modelling

The target technology is converted into function model for further analysis. Since the target technology is more relevant to a procedural method rather than a equipment or device, the Process Model (PM) provided by Goldfire Innovator™ is adopted for function modeling and technology representation of the target technology. Figure 6 shows the PM of the target technology based on the construction method described in the last step. Notice that Provide Link (Prv) implies that the preceding process provides inputs for the successor process; while Corrective Link (Co) implies that the preceding process corrects (or modifies) the functions for the successor process.

In Figure 6, the first step (Clean deteriorate material of pit-hole) provides working space for the second and the third steps; and the last step (Roller compacting) corrects the work results of the fourth step (Fill in hot-mixed AC material).

(4) FM Modification

It was identified by RCA that the root cause for “inaccurate material supply” is “inaccurate measurement”. This problem happens at the fourth step of the PM in Figure 6. The computer aided innovation tool (with Goldfire Innovator™) suggests that a new alternative can be developed to substitute the original method. Applying the contradiction matrix of TRIZ, it is obtained that “Improving EP-28 (measurement accuracy)” results in “Deteriorating EP-25 (waste of time)”. The suggested inventive principles (IPs) are “IP-24: Mediator”, “IP-34: Rejecting and Regenerating”, “IP-28: Replacement of Mechanical Syste”, and “IP-32: Changing the Color”. Considering the above principles, a new operation is adopted to replace the fourth step in Figure 6. The resulted modified process model is shown in Figure 7. Notice that the “Fill in hot-mixed AC material” of the original process is replaced with a new operation. The new operation of the fourth step adopts a laser scanner and associated software to measure the volume of required fill-in AC material; the material is supplied with an automated equipment. Such conceptual alternative will be realized in Method Design.

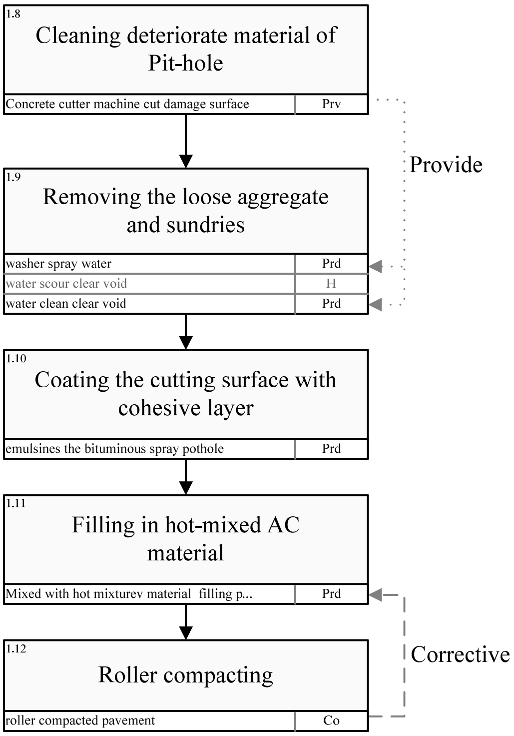

Figure 6 Process Model of the target technology

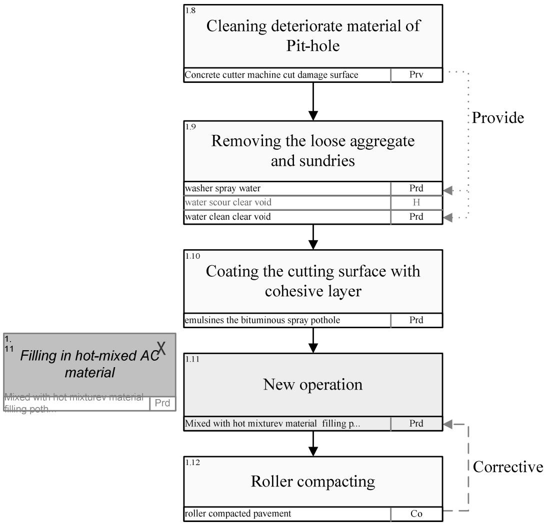

Figure 7 Modified PM

The idea of new operation can be generated by requesting the Knowledge Database with "How to fill the pothole?", the suggested solutions are shown in Figure 8. In Figure 8, four solutions are suggested: (1) Obstacle size affects reflected wave intensity—a wave intensity sensor can be employed to detect the obstacle; (2) Infrared radiation detects roadway surface elevations—Infrared radiation device can be employed; (3) Reflected light detects road irregularities—light detector can be employed; and (4) Laser pumping device—suggesting that laser device is applicable. The fourth solution was obtained by tracing back the "Effect Chain" of the Science Effect database, which illustrates the underlying principle of the first three solutions.

Similarly, four published patents were suggested by Goldfire Innovator™: (1) US 5294210-Automated pothole sensing and filling apparatus; (2) US 5439313-Spray patching pavement repair system; (3) US 6821052 B2-Modular, robotic road repair machine; and (4) US 4511284-Pothole patcher. These are shown in Figure 9.

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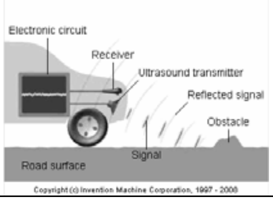
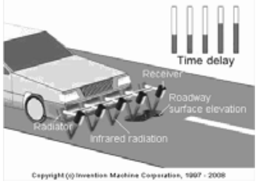
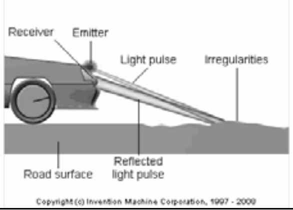
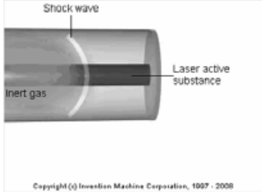
|  |  |
| (1) Obstacle size affects reflected wave intensity | (2) Infrared radiation detects roadway surface elevations |
|  |  |
| (3) Reflected light detects road irregularities | (4) Laser pumping device |

Figure 8 Solution suggested by Sciecne Effect database

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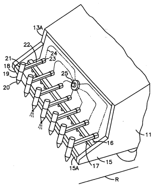
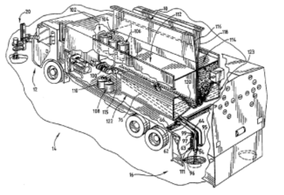
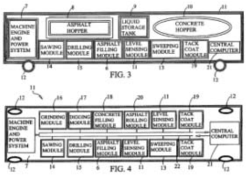
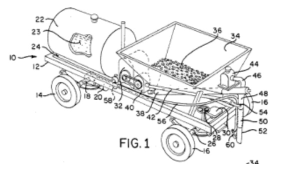
|  |  |
| (1) US 5294210 Automated pothole sensing and filling apparatus | US 5439313 Spray patching pavement repair system |
|  |  |
| US 6821052 B2 Modular, robotic road repair machine | US 4511284 Pothole patcher |

Figure 9 Solutions suggested by previous patents

(5) Alternative Evaluation

The alternative evaluation is performed qualitatively with the domain experts in terms of functionality, constructability, and cost effectiveness. The evaluation results are shown in Table 2. The measurement of required material volume and material supply of the original technology was performed manually by the laborers. They are replaced by automatic equipment and technology. As a result, the functionality and constructability are improved. However, the new operation requires additional equipment, which will increase the cost, and thus the inferior cost effectiveness.

Table 2 Evaluation of the innovated technology

| Criterion | Technology | |
|---|---|---|
| | Original | Innovated |
| Functionality | Medium | Good |
| Constructability | Medium | Good |
| Cost effectiveness | Good | poor |

(6) Method Design

In this step, the implementation method for the conceptual innovation technology is designed. The Computer Aided Innovation (CAI) tool, Goldfire Innovator™, is counseled again to generate design scenarios. From Figure 8 and 9, the IP-28 of TRIZ suggests that a laser scanner can be employed for measurement of the pit-hole volume and required material; similarly, the IP-24 suggests that computer software can serves as mediator that can improve the accuracy of measurement and supply of required material. Both of the two functions are available in the Science Effect and patent databases. However, there has been no design to combine the two functions in road repairing. A conceptual design of the innovated technology is shown in Figure 10.

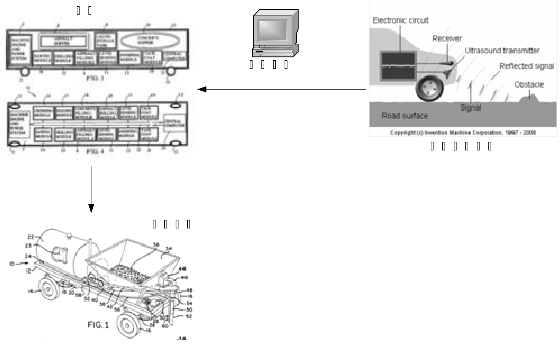


Figure 10 Method design of the innovated technology

(7) Prototyping

The innovated technology has not been physically implemented yet, but a prototype illustration of the innovated technology is shown in Figure 11. The prototype technology consists of four major components: 1) a laser scanner—that detects and scans the pit-hole; 2) a AC material remover—that cleans and removes the deteriorate material of pit-hole scans the pit-hole; 3) a computer with required software—that calculates the volume of pit-hole using the scanned data; and 4) an AC patcher—that fills in AC materials with the required volume and compacts the surface.

(8) Experiment and Testing

Until the deadline of paper submission, the prototype technology was not experimented and tested yet. It will be part of future work. A patent application for the innovated technology is filed to the Taiwan Intellectual Property Office (TIPO) after conceptual design is finished.

## 5. Conclusions

In the paper a proposed STIP method for fast innovation of construction technologies is described in details. Unlike the traditional simulation-based technology improvement techniques, the STIP method generates alternative technologies based on inventive problem-solving techniques (e.g., TRIZ) and technology databases (e.g., Science Effect and patent databases). As a result, it achieves the “radical” or “system” innovation of construction technologies as classified by Slaughter [4].

A process innovation case study of STIP to innovate the pit-hole repairing technology of AC road pavement is conducted to verify and test the proposed STIP. By following the STIP procedure, an innovative alternative for the target technology is successfully generated and designed. It is concluded that the proposed STIP method is feasible and applicability for innovation of process type technology such as road pavement repairing. It is convinced that such method can also be employed to innovate other types of construction processes and technologies.

Although the conceptual prototype of the innovated technology has been developed, real world implementation and experiment should be conducted to verify the proposed prototype. This will become the future works. Moreover, evaluation of the innovated technology was performed qualitatively in this paper, quantitative evaluation will be performed with the technology experiment and testing in future works, too.

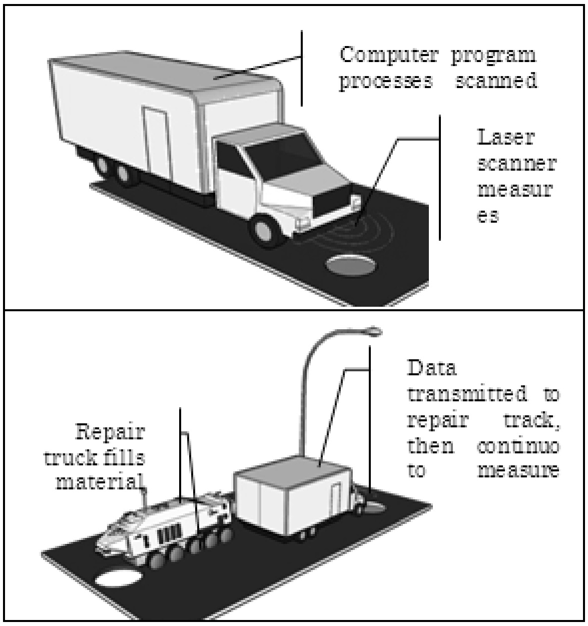


Figure 11 Illustration of the innovated technology

## *References*

[1] Tatum, C. B. (1987). "Process of innovation in construction firm," J. Constr. Engrg. and Mgmt., ASCE, Vol. 113, No. 4, 648-663.
[2] Shin, H., Watanabe, H., and Kunishima, M. (1989). "A new methodology for evaluating a new construction technology from the viewpoint of constructability," Proceedings of the 47th Doboku Gakkai Rombun-Hokokushu, Japan Society of Civil Engineers April 1989, JSCE, Japan, 4 pp.
[3] Harris, R. B. (1992). "A Challenge for Research," J. Constr. Engrg. and Mgmt., ASCE, Vol. 118, No. 3, 422-434.
[4] Slaughter, E.S. (2000). "Implementation of construction innovations," Building Research and Information, Vol.28, No.1, p2-17.
[5] Yu, W. D., Wu, C. M., and Lien, W. C. (2008). "Fast innovation of construction technologies with computer aided innovation tools," Proceedings of International Symposium on Automation and Robotics in Construction 2008 (ISARC 2008), June 27~29, 2008, Vilnius, Lithuania, pp. 521~527.
[6] Halpin, D. W. (1993). "Process-based Research to Meet the International Challenge," J. Constr. Engrg. and Mgmt., ASCE, Vol. 119, No. 3, 417-425.
[7] Yu, W. D., and Skibniewski, M. J. (1999). "Quantitative constructability analysis with a neuro-fuzzy knowledge-based multi-criterion decision support system," Automation in Construction, 8(5), 553-565.
[8] Ioannou, P. G. and Liu, L. Y. (1992). "Advanced Construction Technology System—ACTS," J. Constr. Engrg. and Mgmt., ASCE, Vol. 119, No. 2, 288-306.
[9] Halpin, D. W. (1977). "CYCLONE: method for modelling of job site processes," J. Constr. Div., ASCE, Vol. 103, No. 3, 489-499.
[10] Liu, L. Y. (1995). "Simulating construction operations of precast-concrete parking structures," Proceedings of the 1995 Winter Simulation Conference, 1004-1008.

[11] Martinez, J. C. and Ioannou, P. G. (1994). "General purpose simulation with STROBOSCOPE," Proceedings of the 1995 Winter Simulation Conference, 1307-1313.

[12] Rothe, C. A. (2006). "Using Patents to Advance the Civil Engineering Profession," Civil Engineering, ASCE, June 2006, 66-73.

[13] Yu, W. D., Cheng, S. T., Shie, Y. L., and Lo, S. S. (2006). "Benchmarking Technological Competitiveness of Precast Construction through Patent Map Analysis," Proceedings of International Symposium on Automation and Robotics in Construction 2006 (ISARC 2006), Session B2—Design, Planning and Management System, Oct. 3~5, 2006, Tokyo, Japan, pp. 119~123.

[14] Cheng, S. T., Yu, W. D., Wu, C. M., Chiu, R. S. (2006). "Analysis of Construction Inventive Patents Based on TRIZ," Proceedings of International Symposium on Automation and Robotics in Construction 2006 (ISARC 2006), Session B3—Construction Planning and Management Methods, Oct. 3~5, 2006, Tokyo, Japan, pp. 134~139.

[15] Mohamed, Y. and AbouRizk, S. (2005). "Technical Knowledge Consolidation using Theory of Inventive Problem Solving," J. Constr. Engrg. and Mgmt., ASCE, Vol. 131, No. 9, 993-1001.

[16] Mohamed, Y. and AbouRizk, S. (2005). "Application of the Theory of Inventive Problem Solving in Tunnel Construction," J. Constr. Engrg. and Mgmt., ASCE, Vol. 131, No. 10, 1099~1108.

[17] Altshuller, G. (2002). 40 Principles: TRIZ Keys to Technical Innovation, Technical Innovation Center, Boston, MA, USA.

[18] Li, Y., Wang, J., Li, X. L., and Zhao, W. (2007). "Design creativity in product innovation," International Journal of Advance Manufacture Technology, Vol. 33, p213-222.

[19] TPMA (2007) International R&D Project Management Body of Knowledge, Taiwan Project Management Association, Kaohsiung, Taiwan. (in Chinese)

[20] USPTO, (2008). Web Site, http://www.uspto.gov/, United States Patent & Trademark Office, visited 2008/3.