FIELD TRIALS OF RFID TECHNOLOGY FOR TRACKING PRE-FABRICATED PIPE SPOOLS

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Abstract: The FIATECH Smart Chips project, in conjunction with Shaw Pipe Fabricators and Fluor Corporation, undertook field tests of current RFID technology to determine its technical feasibility for automatically identifying fabricated pipe spools in a laydown yard and tracking shipment through portals. The results indicate the technology could work effectively in the field environment and that it has reached the stage where it can begin to be used to reliably track materials through major portals. Currently, the authors are assessing its potential economic benefits based on preliminary information on recent industrial projects and data provided by the literature.

Keywords: Automated Data Collection, RFID, Technical Feasibility, Materials Management.

1. INTRODUCTION

Of the elements that comprise a constructed facility, construction materials may account for 50-60% of the total cost of a construction project. Materials for a construction project can be classified into three categories: off-the-shelf, long-lead bulks, and engineered items [1]. The different categories of materials vary in cost, delivery lead time, and interchangeability. Generally, engineered items are available at higher costs in smaller quantities and with more unique properties, thus implying longer lead time and requiring more front-end planning.

1.1 Piping Function and Practice

Among engineered materials, pipe spools are of particular interest to industrial projects as piping has been recognized as a very critical yet most costly and least efficient process [2]. Industrial process facilities often involve hundreds or thousands of pipe spools, many of which are unique in material (e.g., cast iron), shape, finish, and other properties (even final installation location on site). In an average size (US$200-300M) industrial project, there may be as many as 10,000 pipe spools [3].

Many industrial projects are on fast-track, due to the pressing need to bring products to the markets fast. Given this characteristic, some industrial projects may take the opportunity to fabricate pipe spools off-site while prerequisite works on site are making progress. In fact, piping has seen significant increase in the use of prefabrication and preassembly over the preceding twenty years [4]. However, piping in fast-track projects still poses potential uncertainty in deliveries and in completing prerequisite site work, leading to “mis-matches that foul up scheduled work sequences” [2].

Under this uncertainty, materials managers rely on large buffers of pipe spools in an effort to secure flexibility in workable backlogs so that they have “at least 60 percent of all pipe on site when 20 percent of the pipe had been installed” [5]. Such large buffers of pipe spools are built in a constructor’s laydown yard from deliveries received 5 to 6 months prior to scheduled installation, and received pipe spools reside in the laydown yard until requisition from pipe fitting crews.

Ultimately, laydown yard personnel will find and stage requisite pipe spools to the crew’s work area for installation. In some cases, they may not be able to locate pipe spools in the laydown yard within a reasonable time and have to search for the “misplaced” pipe spools not only in their own premises but also, for instance, in pipe fabricator’s storage areas. Misplaced pipe spools for a single project may only amount to 2 percent of all pipes [3], but this turns out to be 200 pipe spools for the average size industrial project involving total 10,000 spools.

1.2 Potential Enabling Technology

In the context described above, it is not surprising that field materials management was identified by a recent construction technology needs assessment as one of the areas with the greatest potential for improvement and the greatest positive development impact on engineering construction work processes [6]. Another study supported the notion that RFID (Radio Frequency Identification) technology may assist in streamlining the material management process in the construction industry, although use of the technology in several pilot tests was confined to material receiving at laydown yards [7].

Like barcodes, RFID is an automated data capture (ADC) technology for identifying, locating, or tracking objects or assets and people, but presents several advantages over barcoding in that it does not require physical contact, line-of-sight, or clean environments devoid of noise, contaminants, glare and dirt.

RFID technology has already seen significant beneficial applications in manufacturing, retailing, and transport and logistics industries [8]. Meanwhile, recent developments in RFID technology have addressed many of the technical limitations that prevented it from working effectively in the construction field environment.

2. OVERVIEW OF FIELD TESTS

In response to the compelling opportunity presented in recent construction industry research and recent advances in RFID technology, the FIATECH (Fully Integrated and Automated Technology) Smart Chips project, in conjunction with Shaw Pipe Fabricators and Fluor Corporation, undertook the field tests of current RFID technology. The primary objective of the tests was to determine the current technical feasibility of using RFID technology to automatically identify fabricated pipe spools (and other information about them) in a laydown yard and through a shipping portal as part of realistic transport environments.

The field tests were conducted in two phases that span from September 2003 to March 2004, to allow a staged assessment of RFID capability in field construction application. Phase I was intended to document technical issues and learning related to the envisioned applications of RFID technology. Based on the findings of Phase I, Phase II was conducted to determine the reliability of RFID technology to automatically identify individual pipe spools as they pass though portal gates in typical transportation conditions (flatbed trailer shipments).

There were many technical issues critical to the construction application to be addressed, including: 1) the RF signal read ranges, which typically need to be longer than in current common commercial RFID applications, 2) metal interference, which has been a problem in many common RFID applications, 3) tag attachment to pipe spools and density (reading signals from many tags in a congested area), and 4) inability to control the position of RFID tags relative to the readers. In order to best assess the capabilities of RFID technology in addressing these issues, recently developed active (as opposed to passive) RFID systems were tried throughout the field tests.

3. DESCRIPTION AND RESULTS OF PHASE I

The Phase I trials were conducted using two different types of RFID systems, equipped with handheld and fixed readers. The handheld system was used in determining the ability to read signals at long distances and around metal in manual receiving and inventory applications. The handheld reader included a reader in PC card format and an antenna that were inserted in a handheld PC and could be carried around a laydown yard or flatbed trailer (see Fig.1).

Figure 1. Handheld reader unit

Confirming that read distances and metal interferences could be addressed, a fixed reader system was installed on a portal structure through which a flatbed trailer could be driven, simulating a typical pipe spool transport and receiving application (see Fig. 2). Description of both RFID systems used in Phase I is summarized in Table 1.

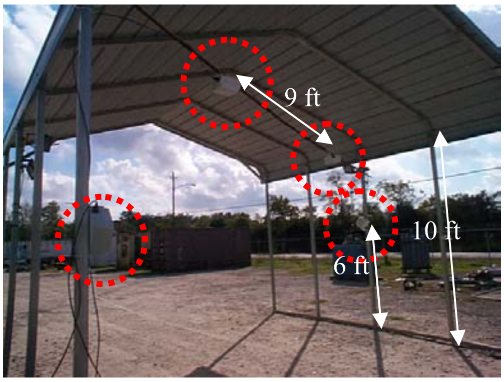

Figure 2. Portal with fixed readers installed

The general test procedure was 1) to have fabrication shop workers place fabricated pipes in a laydown yard and on a flatbed trailer, as they would normally do prior to shipping, 2) to attach RFID tags to individual spools using plastic tie wraps or double sided mounting tape, and 3) to have each RFID system collect unique ID and other information about individual pipe spools when either: a) the handheld

Table 1. RFID technology used in Phase I

	Handheld system	Fixed reader system
Reader (frequency; max. read range)	915 MHz; 20-300 ft depending on types of tags	433.92 MHz; 150 ft
Tag (memory cap.; total no. attached)	64 byte; 12 each	500 KB; 20 each
	8 KB; 12 each	
Tried field conditions	In a laydown yard; around a flatbed trailer while loading pipe spools	While a pipe loaded trailer passed through the portal

reader was carried around about 2-3 ft above the pipe laid down in the yard or loaded on the trailer, or b) the trailer was driven through the portal structure.

For the field trials using the handheld system, RFID tags were attached to 12 individual pipe spools in a variety of sizes and shapes so that most of them were positioned where readers would not be in direct line of sight and/or tag RF signals could be more difficult to reach the readers during the tests (e.g., under large pieces, or on very congested pallets). The results of field trials using the handheld system indicated that current active RFID technology could function well enough in a congested, highly metallic environment to improve efficiency in manual receiving and inventory applications where relatively long read range is desirable. The only difficulties in reading tags in the trials seemed to develop when either: 1) tags were fully surrounded by solid metal (e.g. placed more than an inch or two inside of a spool, or shielded completely by multiple layers of spools), especially with the reader's RF power lowered, 2) or tags were placed in full contact with a surface such as flat metal plate, concrete beam, and the ground. Detailed test logs can be found in [9] that record each trial of reading tags with different placement under varying RF power.

For the field tests with the fixed reader system (or "portal" system), 20 RFID tags were attached to fabricated pipe spools after quality inspection, and loaded on a flatbed trailer to be driven under the portal equipped with four readers (Fig. 2). In addition to the unique ID number of tag, such data as piece marked number, spool number, sketch number, and purchase order number for each pipe spool had been written to tags. The tests were conducted under presumed shipping en route to a construction site, with varying conditions; 1) the density of tags on the trailer, 2) the amount of tag data to be captured - ID only or additional data mentioned earlier, 3) movement of trailer under the portal - pass through or stop-and-go at different speeds, and 4) the number of readers activated - all of the four, those two on top or side, or only one on top center of the portal.

Though limited to general understanding of performance of portal systems, the results of field tests indicated it is technically tractable using current RFID technology to automate tracking the shipping and receiving of fabricated pipe spools beyond simple identification, in typical transport conditions. In the field trials, ID and other information about pipe spools were captured from more tags when the trailer stopped for a short time under the portal, allowing the readers more time (if in order of seconds) to read data. Using multiple readers seemed to be helpful in collecting all tag data, but one reader on top center was sufficient for identification purpose only, provided that the trailer stopped under the portal and then proceeded slowly through it. For more information on the field tests, see [9].

4. DESCRIPTION AND RESULTS OF PHASE II

Phase I has addressed many technical issues related to applications of current RFID technology in shipping and receiving the deliveries of pipe spools, and indicated further trials were warranted. Phase II was pursued to determine the reliability of the technology in such an application that would enable automated identification of individual pipe spools as they pass through a portal, or "portal" application, to some statistical significance. Phase II field trials were conducted using a fixed reader system with the same types of tags as in the handheld system of Phase I, but with a fixed reader (Fig. 3) connected to each of four directional antennas on a portal. Detailed description of the technology used in Phase II can be found in [3].

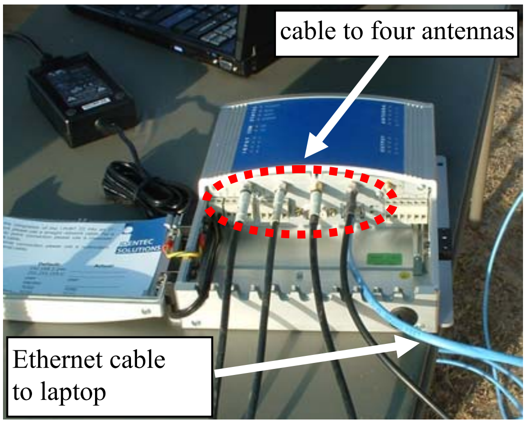

Figure 3. Fixed reader used in Phase II

The Phase II test procedure involved the set up process similar to that of the portal system in Phase I, and testing technical performance of the technology started by determining values of several parameters that form a particular set of field conditions. The test parameters supposed to have some impact on technical performance included those for the fixed system in Phase I, and can be divided into two categories, according to the relative degree of freedom to change their values, as shown in Table 2. Values of the parameters in category Static are relatively hard to meaningfully change since it would not only require much time and effort but affect the fabricator's tight delivery schedule. As such, each parameter in category Static was set to a uniform

Table 2. Categories of Test Parameters in Phase II

Category	Governing level	Test parameters
Static	Test bed	Type and no. of tags Tag positions relative to antennas
Dynamic	Group of trips	Timing of reader activation/deactivation Travel speed of trailer No. of enabled antennas

value over one or two days of field tests, or “test bed”, governing technical performance at a high level. Though limited, changing the relative tag positions has been attempted by moving tags around spools or by reversing the traveling direction of the trailer through the portal.

On the other hand, each parameter under the Dynamic category was given different values within a test bed, but expected to have some constant value across a group of trailer passes (or “trips”) in the same test bed. For instance, one trip in a test bed was involved with the same type and total number of tags as any other trips in the same test bed, but may be characterized by a different travel speed than some trips in the same test bed.

Phase II have completed four days of field tests and total 70 passes have been made, as shown in Table 3 (superscripts to the total number of tags means different types of tags).

Table 3. Overview of Phase II Field Tests

Test bed no.	Total no. of tags attached	No. of active antennas	No. of trips
1	83^q	4	12
2	50^d	4	20
3	56^q	4 or 2	38
Total			70

In determining technical feasibility of the technology for the portal application, the read rate is used as a metric to assess the ability to identify pipe spools accurately and precisely as the shipment of load departs or arrives through the portal. The read rate measures in percentage how many *different* tags of the total loaded are read in each pass. Since in a single trip, tags could be read more than once via any one of the active antennas, the duplicate read ratio is defined to measure how many times a particular tag is read in each trip. Table 4 summarizes the metrics resulting from each test bed. The median read rate is the ‘middle’ read rate, so exactly a half of the trips in the test bed resulted in the read rate greater than the median read rate.

Table 4. Summary of Read Rates and Read Ratio

Test bed no.	Mean read rate	Mean duplicate read ratio	Median read rate
1	98.1%	1.4	98.8%
2	96.4%	1.9	98.0%
3	96.0%	6.8	100.0%

Test bed 3 has yielded the minimum mean read rate but the maximum median read rate. The read rate of 38 passes in test bed 3 had the most skewed distribution with several extreme cases (outliers), as can be seen from the box-whisker plot of mean and median read rates in Fig. 4 (means are marked as diamond dots, medians as vertical lines in the box, and outliers as square dots). One possible explanation of this skewed distribution is that test bed 3 has undergone highly dynamic test conditions which arose from parameter values being more actively changed. Test bed 3 also resulted in the largest duplicate ratio, close to 7. It means that if read at all, a single tag was read on average 7 times in each pass. Perhaps, this high duplicate read ratio is due to the reader’s RF power set to the maximum that made it so sensitive to RF signals transmitted from tags. By the same token, this may have increased the reader’s burden to handle 7 times more data (essentially redundant) received from tags, presumably resulting in the lowest mean read rate.

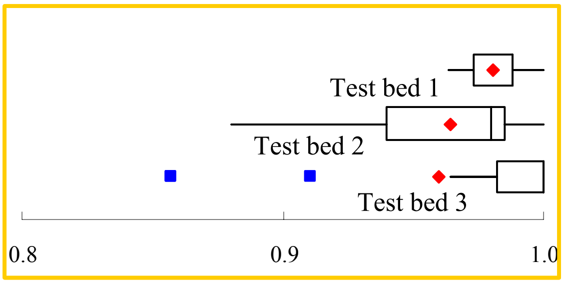

Figure 4. Box-whisker plots of mean and median read rates

Nonetheless, the impact of RF power/sensitivity (reflected by duplicate read ratio) on read rate (or the number of *different* tags read) remains inconclusive, given the limited amount of data. Plotting a pair of duplicate read ratio and read rate for each pass (Fig. 5), it appears that a higher duplicate read ratio is associated with a larger number of *different* tags read, for all the three test beds (the slopes are all positive). Yet this apparent association may not be generalized to say “the more power, the better”. Note each test bed involved different values of Static parameters that could not be controlled across other test beds. Indeed, the test bed 3 with RF power set to maximum yielded a lower read rate on average than the other test beds.

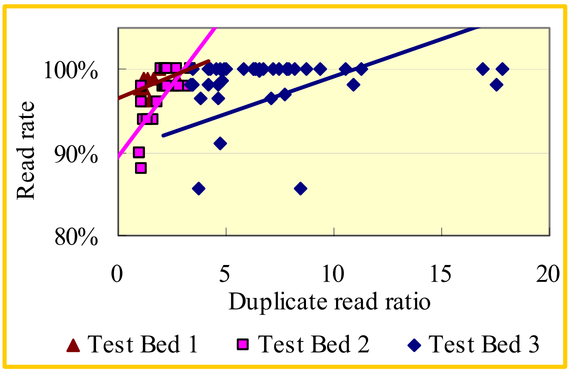

Figure 5. Pairwise scatter plot of duplicate read ratio and read rate

Another interesting observation from Fig. 5 above is the slope of the fitted line for Test bed 2 is steeper than that of Test beds 1 and 2. If slopes for each test bed are thought of as the strength of the relationship between duplicate read ratio and read rate, the steeper slope says the read rates in Test bed 2 were more sensitive to the reader's RF power. In fact, only Test bed 2 tried those tags with a shorter read range, while the other test beds were dedicated to the other type of tags. Thus, with a small change to RF power, shorter range tags would end up with a rather large gain or loss in the number of tags read. Admittedly, this does not convey any statistical significance for the same reason stated earlier.

The variability of read rates in Test bed 3 has lent itself to further analysis, but the sample that arose from Test bed 3 is not totally random. The read rate of one pass is dependent on the outcome of the previous pass to some degree, because of a consistent effort to increase read rate by selectively changing some of the previous parameter values. Thus, 38 passes from Test bed 3 were re-organized into groups that have the similar values for some test parameters, as shown in Table 5 (several passes did not fall into any of the groups). Moving from group I to V, the mean read rate tends to increase while the variance of read rate is decreasing (see also Fig. 6). This observation suggests that under the set of field conditions classifying trips into group IV or V, the technology under consideration is most likely to achieve 100% reading of 56 tags every time the load of pipe spools is shipped/received through the portal.

The question is whether the field test data supports the assertion that the differences of the mean read rates between groups of trips are statistically significant. This question is answered by means of statistical hypothesis tests on the differences in mean read rates between comparable groups; 1) groups I and IV, 2) groups II and IV, and 3) groups II and III. Statistical hypothesis testing usually requires some test statistic to define a rejection region from the sample space where the null hypothesis (H_0) is rejected and hence the alternative hypothesis (H_1) accepted. Now we derive a test statistic.

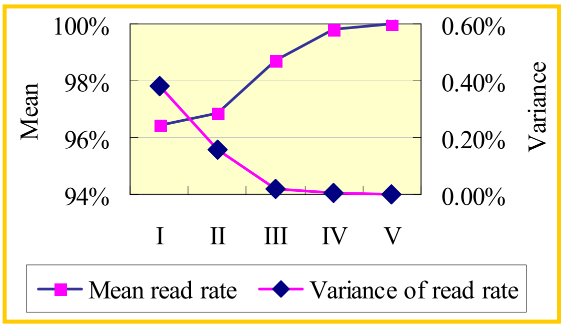

Figure 6. Mean and variance of read rates

Let p_i denote the probability that each tag will be read (i.e., the read rate) during passes of Group i, and each tag is assumed to have the same p_i in every pass under the field conditions characterized by Group i. Then the number of tags of the total 56 that are read in each pass of Group i, Y_i has a binomial distribution with parameters 56 and unknown p_i, or $Y_i \sim$ Bin[56, p_i]. Further, let n_i denote a sample size of Group i (i.e., the number of trials or trips, e.g., $n_1 = n_4 = 9$), and Y_{ij} the number of tags read in jth pass of Group i. Then observed values of $Y_{i1}, Y_{i2}, \ldots, Y_{in_i}$ would have yielded a random sample of size n_i since 1) they arise from the identical binomial distribution and 2) every Y_{ij} is independent of one another provided that the underlying dependency between successive trials has been addressed by the reconstruction of the overall sample. Y_{ij} can then be added up to represent the number of tags read for Group i as a whole, without loss of randomness, and approximated to a continuous Normal random variable:

$$\sum Y_{ij} \sim \mathrm{Bin}[56n_i, p_i] \approx \mathrm{N}[56n_ip_i, 56n_ip_i(1-p_i)] \sim Z_i \qquad (1)$$

Manipulating (1) gives us another random variable $Z_i/(56n_i) \approx \mathrm{N}[p_i, p_i(1-p_i)/(56n_i)]$, which represents the read rate for Group i (note its mean is p_i). Finally, the statistic Z_{ij} given by standardizing $Z_i/(56n_i)– Z_j/(56n_j)$ is used to test the null hypothesis H_0: $p_i = p_j$ (no difference in mean read rates between Groups i and j) against H_1: $p_i < p_j$. Table 6 shows there is a statistically significant difference between Groups I

Table 5. Test Bed 3 Decomposed into Groups of Trips

Group no.	No. of trips	Reader on/off timing (before/after trailer front/rear end)	Travel speed	No. of antennas; traveling direction	Mean read rate	Variance of read rate
I	9	5~6 m; 6~7 m	1 mph	2; counter-clockwise	96.4%	0.383%
II	4	5 m; 3~9 m	5 mph	4; counter-clockwise	96.9%	0.157%
III	7	0 m; 2 m	4~5 mph	4; either direction	98.7%	0.018%
IV	9	5~6 m; 6~7 m	1 mph	4; counter-clockwise	99.8%	0.004%
V	6	0 m; 0~1 m	2 mph	4; clockwise	100.0%	0.000%

Table 6. Hypothesis Test Result for Groups I and IV

Group no.	No. of trips	Reader on/off timing	Travel speed	No. of antennas; traveling direction	Mean read rate	Z_{14} $Z_{0.01}$
I	9	5~6 m; 6~7 m	1 mph	2; counter-clockwise	96.4%	-3.968 < -2.326
IV	9	5~6 m; 6~7 m	1 mph	4; counter-clockwise	99.8%	Reject H_0

and IV (at significance level α=.01). The results for other groups are in Tables 7 and 8. The results of hypothesis tests showed that the number of antennas enabled and the truck traveling speed have a significant impact on the read rate and that the read activation duration does have some effect on the read rate, but not as significantly.

Table 7. Hypothesis Test Result for Groups II and IV

Group no.	No. of trips	Travel speed	Mean read rate	Z_{24} $Z_{0.01}$
II	4	5 mph	96.9%	-2.482 < -2.326
IV	9	1 mph	99.8%	Reject H_0

Table 8. Hypothesis Test Result for Groups II and III

Group no.	No. of trips	Reader on/off	Mean read rate	Z_{23} vs. $Z_{0.05}$
II	4	5 m; 3~9 m	96.9%	-1.430 > -1.645
III	7	0 m; 2 m	98.7%	Accept H_0

However, it should be noted that the small sample size n_i restricts the credibility of the statistical hypothesis tests. For optimal credibility, samples of size larger than 100 would have been required of our normal approximation to the binomial distribution of $Z_i/(56n_i)$ so that $p_i \pm 2\sqrt{p_i(1 - p_i)/(56\,n_i)}$ can lie in the interval (0, 1) [10].

5. CONCLUSIONS

To assess the technical feasibility of RFID technology in the construction industry, the field tests have been conducted as part of the FIATECH Smart Chips project. The field trials were primarily concerned with such applications that would improve efficiency in manual receiving and inventory of fabricated pipe spools in laydown yards and automatically track the shipments at major portals located in the supply chain.

Phase I field tests have addressed many technical issues related to the envisioned applications, and the results indicated that current active RFID technology could function effectively in the construction field environment involving large metal objects and requiring relatively long read range. Furthermore, Phase II field trials tested the reliability of the technology in the portal application to automatically identify pipe spools in typical transportation conditions, and the results showed with limited credibility that the current technology can achieve 100% accuracy and precision under a certain set of field conditions which can be accommodated by the potential users.

In addition to the technical feasibility of RFID technology, potential economic benefits should also be assessed before implementation of the envisioned applications. The authors have identified several promising areas in the current work process, and are currently assessing the overall economic benefits possible by implementing the applications of RFID technology.

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