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Integrating Wearable Sensor Technology into Project-management Process

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Abstract: A sensor-based project management process, which uses continuous sensing data of face-to-face communication, was developed for integration into current project management processes. To establish a practical process, a sensing system was applied in two software-development projects involving 123 and 65 employees, respectively, to analyze the relation between work performance and behavioral patterns and investigate the use of sensor data. It was found that a factor defined as "communication richness," which refers to the amount of communication, correlates with employee performance (job evaluation) and was common in both projects, while other factors, such as "workload," were found in just one of the projects. Developers' quality of development (low bug occurrence) was also investigated in one of the projects and "communication richness" was found as a factor of high development quality. As a result of this analysis, we propose a four-step sensor-based project management process, which consists of analysis, monitoring, inspection, and action, and evaluated its effectiveness. Through monitoring, it was estimated that some "unplanned" events, such as changing specifications and problem solving during a project, could be systematically identified. Cohesion of a network was systematically increased using a recommendation of communication, called WorkX, which involves micro rotating of discussion members based on network topology.

Keywords: sensor network, communication, behavioral science, project management, performance analysis

1. Introduction

Standard management procedures are defined in the Guide to the Project Management Body of Knowledge (PMBOK guide) [1], a well known guideline for managing projects. Procedures, such as identification of stakeholders, communication planning, and information distribution, are defined and described in a qualitative manner in terms of communication. Lack of communication often causes problems, such as delay in attaining consensus on specifications, interface errors, misunderstanding of specifications, and delay in understanding the project status. Understanding the state of communication in a project is fundamental. Qualitative description in the guide is, unfortunately, not useful or practical enough in managing actual projects, and there is no tool available yet for helping managers. There are no common answers with regards to several fundamental questions, namely, "When and how much communication is required to improve productivity and quality?," "Who should talk to whom?," and "What kind of communication satisfies employees?." Since these questions are difficult to answer quantitatively, managers rely on their own experiences.

Information technology has been changing people's lives quite drastically in the last few decades. The personal computer has given access to information to "whomever" wants it and cell phones have given us the ability to communicate "wherever" we are. Because of this evolution of information technology, tiny computers are becoming available and collecting information about people without them noticing is possible [2]. A wearable sensing system in the workplace was conceptually proposed [3], [4] and deployed for studying the relation between communication and performance metrics of employees [5]. In our previous study, we also developed a system for sensing communication among employees, called "Business Microscope [6]," and used it in several organizations. Through the several deployment phases of this system, it turned out that we have to develop not only sensing tools but also management processes that use such a sensing system effectively. According to our experience, managers understand that the state-of-the-art sensing system is capable of uncovering something not known yet; however, he (or she) does not have an idea how and when to use the system, and how to change one's project based on the sensed data. Therefore, we propose a four-step sensor-based project management process. To develop such process, a sensor system was applied to two projects to analyze the relation between communication and performance. Our four-step sensor-based management process, which consists of analysis, monitoring, inspection, and action, was developed based on the analysis and interviews of project managers.

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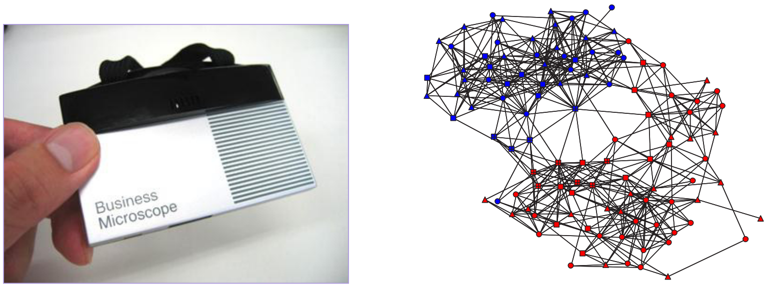


(a) Wearable badge (b) Face-to-face communication network

Fig. 1 Business Microscope.

2. Previous Work

2.1 Human Behavior Analysis

Pentland notes that a person's inner state becomes unintentionally visible as a subtle "honest signal" of motions and voice features, such as activity level, mimicry, influence, and consistency [7]. Researchers have developed several socially aware platforms for measuring different aspects of a social context.

Choudhury designed a wearable sensor package [8] intended for measuring interactions between people by means of an infrared (IR) transceiver, a microphone, and two accelerometers. Madan [9] developed software that learns various aspects of people's social lives by mining their face-to-face and phone interactions. Gips [10] used motion and proximity sensors to identify groups of friends taking part in a career fair, the team membership of students participating in a treasure-hunt game, and the company affiliation of visitors attending a conference. In accordance with recent progress in sensing technology, some researchers have started to continuously capture non-linguistic signals by using electric devices.

The differences in communication media, such as face-to-face and phone interactions, have been studied. Daft and Lengel researched the "information richness" of communication media [11]. Face-to-face communication was found to be richest because it provides multiple social cues through both verbal and body language, which reduce equivocality. The amount of social cues decreases in other media, such as telephone, documents such as written letters or emails. Face-to-face meetings are most effective for communicating ambiguous topics in a short period of time. On the other hand, when information is simple and does not require bi-directional communication, email is suitable. Ara [4] mentions the difference between face-to-face interaction and email in terms of frequency of change. Patterns of physical interaction change dynamically while email is more stable over time. Of course, communicating by email is important, but we primarily focused on face-to-face communication in this research, assuming that emergent and quick communication in project management is face-to-face, by considering information richness and quickness of bi-directional communication.

2.2 Organizational-behavior Analysis and Engineering

Once technology for human behavior analysis was established, some researchers have started to capture non-linguistic signals and analyze organizational behavior of real work settings by combining sensor data and organizational theories. By investigating employee behavior involved in several projects, common practices regarding better performance, production quality, and employee satisfaction can be identified. To obtain a realistic view of an organization, past research has been based on surveys or video recording. Since using these tools is time consuming and costly, the number of samples is limited. For example, Wu et al. used face-to-face networks and proximity data to explain employee productivity [5] by using a badge-shaped platform, which was originally developed at MIT Media Laboratory [12]. They found that a cohesive network topology is associated with higher productivity; in other words, a person who belongs to a more cohesive and meshed communication network tends to complete their task (in this case, system configuration) more quickly.

Olguin proposed interventions based on sensor data [13]. Seating arrangement was supposed to minimize the physical distance among members of each team, as well as the distance between teams that interacted the most. In a hospital, instant feedback of nurses' location, activity levels, and face-to-face communication was proposed for increased productivity.

2.3 Continuous Behavior Monitoring and Feedback System

There has been much progress in sensing technology in the last decade, which enables "24/365" sensing using unobtrusive devices [2]. Such enormous and longitudinal data enables continuous managerial applications.

We previously designed a system called "Business Microscope" for collecting data through a badge-shaped device (**Fig. 1** (a)) and analyzing the data over extended periods of time (Fig. 1 (b)) [6]. This system detects face-to-face interaction by using infrared sensors, as well as motion rhythm and magnitude of acceleration. This system has been used in various organizations (**Table 1**). The first couple of experiments were conducted to visualize organizational structure and analyze the relation between performance and behavior in a small group (twenty employees) over a short sensing period (such as one month or even less). However, user's needs have been brought to a sensing of larger group over a longer period to determine common behavioral patterns across several groups, evaluate organizational management by comparing before and after managerial change, and continuously improve performance. The data have been used for several studies such as analyzing knowledge creation within an organization [14], visualizing relations between communication and solo work [15], and investigating psychological absorption (flow

Table 1 Breakdown of data stored in organizational database.

Target organization/ job function	# of employees	Target organization/ job function	# of employees	Target organization/ job function	# of employees
Think tank/research	75	IT development/ HR management	40	Research laboratory/ HR management	29
Hospital/nurse	32	Research laboratory/ research	70	IT developer/ software development	65
IT developer/ development	60	Social infrastructure/ planning	30	IT developer/ software development	123
Design/researcher	170	Office equipment/ sales and development	83	IT developer/ software development	412
IT developer/ customer support	30	IT developer/ software development	30	IT developer/software development and sales	119

state) [16]. By conducting these large continuous experiments, the total amount of data collected to date has increased to over a hundred-thousand man-days.

Business Microscope has two major functions.

(1) Visualization

Communication data can be used to depict a communication network, as shown in Fig. 1 (b). Each circle represents a single employee. If communication exists between two employees, their circles are connected by a line, the thickness of which represents the total amount of communication between those two employees. Glancing at this network makes it possible to quickly grasp the key structure of an organization; for instance, member roles (i.e., who communicates often and who connects to other members), team characteristics (i.e., which teams communicate most/least), and communication between teams (i.e., where is a functional silo, communication gap between employees).

(2) Behavior and performance analysis

Sensor data can be used to characterize each organization, team, and individual from various viewpoints. A typical viewpoint is the amount of communication. However, more sophisticated viewpoints are topology of a communication network, interaction patterns during conversation, patterns of motion rhythm, and time consumed for each activity such as communication, solo work, and out-of-office duties. There are over 200 behavioral factors. In this analysis, we investigated the relation between these parameters and organizational performance-related response variables (i.e., productivity, product quality, and satisfaction). The goal was to identify behavior that strongly correlates with the performance of an organization.

While continuous behavior monitoring technology have been developed, employees in real work setting are still investigating how and when to use the technology, and how to change one's project based on the sensed data. This research aims to provide practical project management processes based on the continuous behavior monitoring technologies. We primarily focused on systems for software project management because measuring performance is straightforward and the systematic monitoring process is already incorporated in the management structure. Once the system is established, our focus can be broadened to the other routine work, such as in hospitals or call centers, and non-routine work.

3. Experimental Setting

3.1 Purpose of Experiments

To establish a sensor-based project management process, we carried out a series of experiments in two projects at a software-

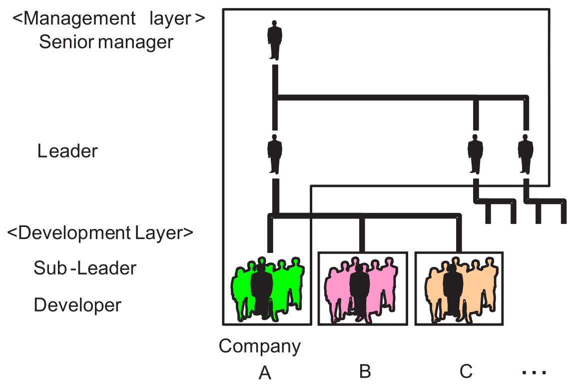


Fig. 2 Structure of target project.

development company. The first purpose of the experiment was to clarify the relation between employees' performance and behavior in two different projects for building a practical management process. It is generally said that communication is important, however, there is no common, quantitative proof of this. Analyzing just two projects is not sufficient from a statistical point of view, but we are able to gain common insight on the relation between performance and behavior. In this research, we focused on three key roles in a project, manager, sub-leader, and developer, and analyzed their behavior and performance. Details of the analyses are described in the next section.

3.2 Organizational Structure

We carried out a series of experiments in two different projects at a software-development company in Japan. The company is developing a large-scale back-office processing system. The basic structure of the two target projects is tree-shaped, as illustrated in **Fig. 2**. Development is managed according to the waterfall process. Each unit at the development layer consists of around ten developers and one sub-leader from the same company. Development units are managed by the main company (company A). The number of employees in each project is summarized in **Table 2**. The company has long been changing management processes and employee behavior for improved productivity.

In managing project, there is still one fundamental difficulty caused by the nature of project, i.e., project volatility. In many projects, the owner of the project brings sufficient managers and developers together as a team at the beginning. In this situation, some employees do not know each other, e.g., their personalities, communication skills, even developmental skills are difficult to understand. However, all employees have to do their best to develop a product by the project deadline. There is always the

Table 2 Number of workers in target project.

(a) Project 1

Position	Company	# of workers
<Management layer>		
Senior manager	A	2
Leader	A	23
Sub total		25
<Development layer>		
Sub-leader,	A	27
Developer	B	18
	C	16
	D	11
	E	7
	F	5
	Others	14
Sub total		98
Total		123

(b) Project 2

Position	Company	# of workers
<Management layer>		
Senior manager	A	3
Leader	A	10
Sub total		13
<Development layer>		
Sub-leader	A	13
Developer	B	10
	C	8
	D	6
	E	5
	F	3
Sub total		52
Total		65

Table 3 Typical activities in each motion rhythm.

Motion rhythm	Typical activities
0Hz	Sleeping; just thinking without movement
0-1Hz	Web browsing; listening
1-2Hz	Talking; typing
2-3Hz	Walking; talking with dynamic gestures
3-4Hz	Excited discussion, rushed walking
>4Hz	Running

potential of misunderstanding and miscommunication. Furthermore, when a project is completed, employees are separately assigned to different projects again, which makes it difficult to improve company-wide knowledge. Senior managers of the target company, therefore, requested the use of wearable sensors in their projects.

3.3 Behavior Measurement

In our previous study, we designed a hardware and software infrastructure, called Business Microscope, to collect and analyze behavioral data over extended periods of time [6] (Fig. 1). The sensor-badge hardware was developed to function at low power and be compact enough (50 grams) to wear over long periods of time. As described in a previous paper, periodical sleep and wake-up functions are built in for longer battery life [6]. A sensor badge wakes up every 10 seconds to collect data. This badge is capable of detecting the following information:

- Face-to-face interaction detected with an IR sensor (detecting interaction between badges within approximately two meters at an angle of 180 degrees)

- Motion rhythm calculated from three-axis accelerator. Acceleration signals are captured for 2 seconds every 10 seconds at 50 Hz. The unique motion rhythm, frequency at those 10 seconds, is then calculated by the number of wave zero-crossings after band-path filtering; for instance, if four zero-crossings are found during the 2 seconds, we determine that the motion rhythm of those 10 seconds is 2.0 Hz. Identifying behavior from rhythm is not in the scope of this research, but **Table 3** lists the typical activities in each rhythm.

Extra data, such as voice energy, temperature, and luminance, are collected through the badge. Such a rich dataset will be useful for analyzing detailed behavior and situations, e.g., in which environmental situation a person become communicative. In this paper, however, we focus on analyzing the amount of face-to-face interactions and a person's motion.

The 17 basic parameters listed in **Table 4** were calculated based on face-to-face interaction and motion data and used as an individual's behavioral parameters.

The data collected through the badge includes limitations and assumptions on communication.

- The topic of each communication is not taken into account. Some communication is not related to business issues. We still assume most communication in the office is related to business because it is difficult to keep talking on other topics in the office due to the presence of one's manager, colleagues, or even customers.

- Communication is not captured when two badges are not facing each other in close proximity, e.g., employees sometimes talk facing back to back or talk from far away. The assumption is that the amount of such communication is very small compared to detectable communication.

3.4 Performance Measurement

The following information for the analysis was collected.

(1) Employee evaluation

The senior managers rated all employees on a scale from one to five based on each employee's capabilities: one is poor, five is best, and three is average. We insisted that the score should represent the total job capability of an employee during the last several months, rather than representing a particular effort or fault in the short term.

(2) Quality of development

It is ideal to measure the quality of an individual employee's productivity, i.e., number of bug reports, and record their behavior at the same time and then to correlate them. However, there are difficulties in doing this due to the following two limitations.

- Total quality of the product is measurable at the end of the project.

- Behavioral data should be collected from the beginning to the end of the project.

If these limitations are precisely followed, there would be few projects available for analysis. Therefore, we assumed the following two premises and used quality information on a project completed within the previous two months.

- An employee's ability, his (or her) behavior, and project mem-

Table 4 Behavioral parameters.

#	Category	Parameter
1	Network	Degree: Number of employees communicated with
2		Cohesion: Density of network (clustering coefficient) weighted by number of employees connected (degree)
3		Distance: Average path length between all pairs of employees on communication network.
4	Communication	Amount of communication: time spent in communication
5		Amount of active communication: time spent in communication with high activity level (i.e. motion rhythm above 2 Hz).
6		Amount of non-active communication: time spent in communication with low activity level (i.e. motion rhythm below 2 Hz).
7		Communication ratio: time spent in communication to time spent in office.
8		Active communication ratio: amount of active communication to amount of communication.
9		Number of employees communicated with in a day (average)
10	Activity	Amount of work: time spent in office
11		Amount of solo work: time spent in activities other than communication
12		Amount of concentration: time spent in solo work with low activity level (motion rhythm below 2 Hz. Threshold was determined through video recording.)
13		Amount of non-concentration: time spent in solo work with high activity level (motion rhythm above 2 Hz)
14	Neighbor	Average score of each parameter (1 to 12) across one's 1-step neighbors (employees communicated with)
15		Standard deviation of each parameter (1 to 12) across one's 1-step neighbors
16		Average score of each parameter (1 to 12) across one's 2-step neighbors (employees reachable in two steps on communication network)
17		Standard deviation of each parameter (1 to 12) across one's 2-step neighbors

bers are similar to those of two months ago.

- An employee's behavior is collected for one month. According to the accumulated data, the ordinary behavior of each employee is characterized; thereby, averaging out exceptional behavior.

3.5 Personality Questionnaire

Companies commonly use personality data in human-resource management. Some use the data to predict job suitability when hiring and some use them for optimizing business training. Psychological studies have shown that human personality has five dimensions, extraversion, agreeableness, conscientiousness, emotional stability, and openness. For instance, Salgado [17] compared several different jobs and found higher conscientiousness in police officers and low emotional stability in skilled employees. Recent research has also found that there is one single hidden factor among the "big five personalities" [18], namely, the "general factor of personality" (GFP), which is supposed to represent a positive mind and social adaptation. In this study, a "big-five questionnaire" [19] translated into Japanese was used for attaining participants' personalities. We then calculated the GFPs of individuals from the big-five scores according to the parameters given by Rushton et al. [18].

4. Analysis Approach

4.1 Analysis of Managers

It is said that the main task of project managers, even up to be 70%, is communication. Accordingly, we measured individual managers' communication behavior and determined whether the data correlate with performance (i.e., employee evaluation described in the previous section).

- *Hypothesis 1: Higher-performing managers engage in a larger amount of communication.*

4.2 Analysis of Developers

The primary goal of developers is to create a high-quality product that meets certain requirements. Since it is important to secure enough time for actual development, time for communication is sometimes neglected. However, constant communication would help uncover problems with a project as well as reduce anxiety and stress of individual employees. This assumption leads to Hypothesis 2 below. We attempted to obtain quality information in project 1, but no meaningful information became available within a reasonable period of time due to the lack of attaining consensus on the "grand truth" of quality, i.e., number of bugs normalized due to development difficulty. Therefore, in project 2, development difficulty was determined by a senior member in the quality control group. From a statistical point of view, the total number of developers having quality information was still small, 17, but analysis was still conducted.

- *Hypothesis 2: Higher-performing developers engage in a larger amount of communication.*

4.3 Analysis of Sub-leaders

To clarify the behavioral factors of a high-performance team, we conducted interviews with the senior managers of project 2.

The main concern was the difference between a successful project and a failed project. The interviews revealed three factors that the senior managers assumed to be important. As illustrated in Fig. 2, the target project included middle managers called "sub-leaders." They are skilled developers whose role is managing a development team, giving daily directions to the other developers, reporting the latest project status to the senior managers, and negotiating help if necessary. In the case of a successful project, all sub-leaders communicate well enough to identify problems in the early phase and solve them. As a result, a sub-leader is able to secure time for their solo development work. In the case of a failed project, problems are only detected when they become critical. Under this circumstance, sub-leaders need to spend a large amount of time and effort in solving the problem. There were not enough sub-leaders to statistically clarify the hypotheses, but analysis was conducted.

- *Hypothesis 3: Higher-performing sub-leaders engage in a larger amount of communication with other sub-leaders.*

- *Hypothesis 4: Higher-performing sub-leaders engage in a larger amount of communication with leaders.*

- *Hypothesis 5: Higher-performing sub-leaders make more time for solo work.*

4.4 Analysis Procedure

To evaluate the above-stated hypotheses, we conducted the following four analyses.

(1) Calculating the 17 basic parameters listed in Table 4.
(2) Calculating the correlation between behavioral parameters, performances (i.e., employee evaluation and development quality), and personality parameters. A behavior or personality parameter was determined as significant if its correlation with performance was high ($p < 0.05$).
(3) Conducting factor analysis (Promax rotation) on the behavioral and personality parameter selected in step (2) to determine hidden factors. The number of factors was determined according to eigenvalues.
(4) Calculating a factor score for each employee and calculating the correlation between the factor score and an individual's performance.

5. Analysis Results

5.1 Basic Statistics

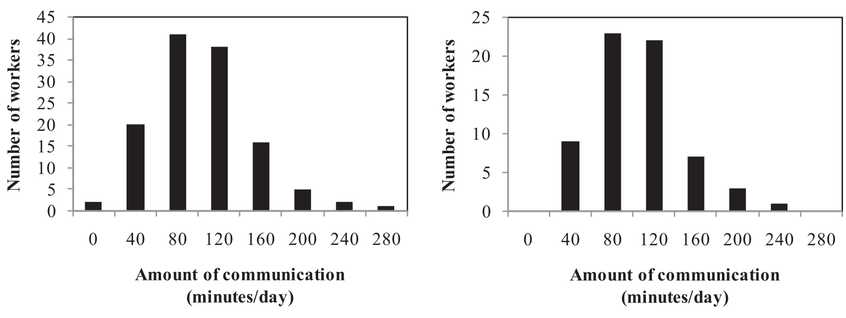
Table 5 lists the basic statistics of communication data, and **Fig. 3** shows a histogram of the average amount of communication of all employees in projects 1 and 2. On average, the employees spent 85 minutes in face-to-face communication per day, communicating among seven employees. Time spent in communication ranged from fifteen minutes to four hours; in particular, 90% of the time range was from forty minutes to three hours. If data has a large amount of irregularities, correlation analysis provides irregular and useless output. However, according to these data, it was assumed that the target project had a regular amount of communication and thus meaningful insights could be drawn from the analyses.

5.2 Analysis 1: Relation between Rating and Behavior

We conducted the above-mentioned four analyses for both projects 1 and 2. In project 2, time spent on solo work, i.e., the total amount of work time minus time spent in communication, negatively correlated with performance, i.e., employee evaluation ($r = -0.61$, $p < 0.01$). In contrast, the amount of communication had a weaker correlation with performance ($r = 0.41$, $p < 0.05$). Throughout the interview with managers, it was assumed that they often visited customers and communicated often outside their offices. A new behavioral feature, called "communication ratio," i.e., time spent in communication divided by work-

Table 5 Basic statistics of communication data.

	Amount of communication (minutes)		Number of employees communicated with (minimum 3 minutes)	
	Project 1	Project 2	Project 1	Project 2
Average	84.1	84.6	6.5	6.6
Standard deviation	45.6	41.2	5.3	4.2
Max	248.0	231.1	24	20
Median	81.0	80.1	6	6
Min	7.0	14.7	0	0



(a) Project 1 (b) Project 2

Fig. 3 Histogram of average amount of communication.

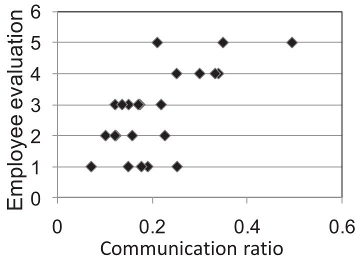


Fig. 4 Relation between managers' performance (employee evaluation by senior managers) and communication ratio in project 2.

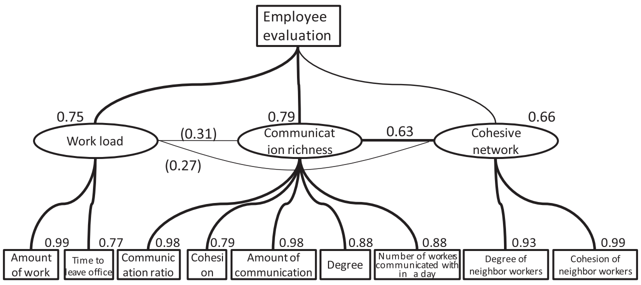


Fig. 5 Relation between managers' performance (employee evaluation by senior managers) and behavior in project 1.

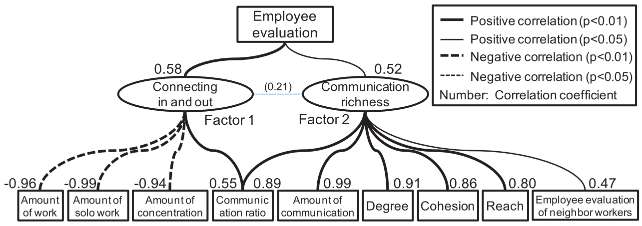


Fig. 6 Relation between managers' performance (employee evaluation by senior managers) and behavior in project 2.

ing hours in one's office, was therefore defined. This ratio has a higher correlation with performance (**Fig. 4**, $r = 0.67$, $p < 0.01$).

Factor analysis was conducted to identify common habitual behavioral features related to employee evaluation (**Figs. 5** and **6**). Three were found in project 1, and two factors were found in project 2. In project 1, the factor referring to long working hours and leaving the office late is called "work load." This means a high-performing manager works hard, but also indicates such a manager gives more opportunities for other employees to communicate with him (or her). Another factor refers to the amount of communication, in particular, time spent in communication, number of employees communicated with, network cohesion, and network reach. This factor is simply called "communication richness." The last factor refers to one's network neighbor, i.e., with whom one often communicates. In particular, the neighbor of a high-performing manager tends to have a higher degree (larger number of employees with whom he/she communicates) and more cohesion (density of network). This might be known from one's experience but striking to see from the data.

In project 2, one factor refers to short working hours as well as a high ratio of communication. This factor is called "connecting in and out" of the office. In contrast to project 1, we assumed that discovering new knowledge from outside and integrating it in the organization for new business was important for project 2. The second factor refers to "communication richness", which is

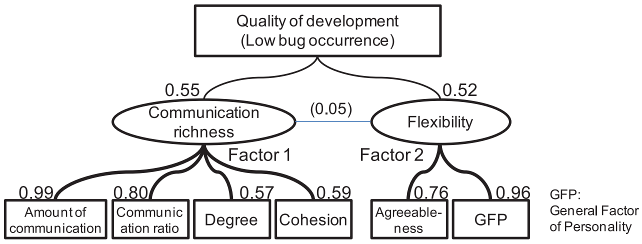


Fig. 7 Relation between developer's behavior and quality of development.

similar to the second factor in project 1. Factor 1 (connecting in an out) correlates with employee evaluation ($r = 0.58, p < 0.01$), as does factor 2 (communication richness) ($r = 0.52, p < 0.05$).

According to the analyses of both projects, there is some difference in the length of work, but we concluded that highly rated managers have a common feature regarding communication, as stated in Hypothesis 1.

5.3 Analysis 2: Relation between Development Quality and Behavior

As illustrated in **Fig. 7**, two factors were found to affect the relation between development quality and behavior. The first factor is related to communication, i.e., total amount of communication, communication ratio, number of employees communicated with, and network cohesion. "Communication richness" is a factor of development quality, as stated in Hypothesis 2. The second factor is related to personality features, i.e., agreeableness and GFP. Since the GFP, as described above, anticipates the adaptability of a person, this second factor represents an employee's "flexibility." According to these two factors, it can be concluded that rich communication and flexibility are key levers of high-quality development under uncertain conditions. Senior manager assumed that behaviors indicating solo work, such as time spent in the office or time spent in activities other than communication, could be related to high quality, but it is intriguing that no such factors were found.

5.4 Analysis 3: Relation between Sub-leader Behavior and Individual's Performance

To evaluate Hypotheses 3 to 5, we calculated the amount of communication with another sub-leader, communication with a leader, and amount of solo work without communication. Through correlation with employee evaluation, the amount of communication with another sub-leader was found to be a factor of high performance, as stated in Hypothesis 3 ($r = 0.79$, $p < 0.01$); however, the other two hypotheses (4 and 5) were not confirmed for the current set of behavioral features ($p > 0.1$). Since a sub-leader often works outside the office, the simple amount of communication might not be the key index of performance; rather, quality of communication, such as bi-directional, constant, and frequent communication, needs to be investigated.

6. Integrating Wearable Sensors in Project-management Process

6.1 Concept of Sensor-based Project Management

As described in the previous section, "high-performance behavior," such as "communication richness," of a target organization was identified. Lack of communication causes errors, but high-performing managers as well as high-quality developers avoid such errors by sufficient communications. Communication is important; however, it is impossible to intensively discuss with all project members due to lack of resources. We therefore investigated a method for effectively accelerating the entire project-management process by using wearable sensors and feedback. Through interviews of skilled managers, the key process of current management and the major problems were found.

(1) Monitoring project status

A senior manager can optimize resources once he (or she) detects a problem, such as a decline in productivity or quality of development of a project, but nothing can be done before that detection. It often requires a week or more to detect a problem. In an actual development process, employees even try to hide a problem from managers when they think they can solve the problem on their own. In this unsatisfactory situation, a senior manager only detects the problem when it has become critical. If the senior manager can visit the office and communicate with the employees, he (or she) might notice such problems, but this is often difficult within the limited time available to him (or her).

(2) Inspection of problems

Once a manager detects that something may be wrong in a project, the cause of the problem and action to solve it is investigated. Problem detection is usually done through discussions with individual employees or intensive meetings among potentially related employees. These discussions are time consuming to both the manager and employees. In most cases, through interviews, the origin of the problem and solution to the problem is communication. Lack of communication or miscommunication between customers and managers, between managers and developers, and among developers are often found to be too common.

(3) Managing change

A manager reinforces insufficient communication and solves problems by asking employees to visit customers or related divisions, establish a series of meetings, or restructuring members and schedules. In addition to such defensive actions, a manager is concerned with constant preventative investigation to improve a project's condition and prevent problems. It could be a quick meeting every morning, rotation of employees, or changing the physical environment.

From the analyses of these key processes, we developed the concept of a four-step sensor-based project-management process (**Fig. 8**). Details of each step and its effectiveness are described in the following subsections.

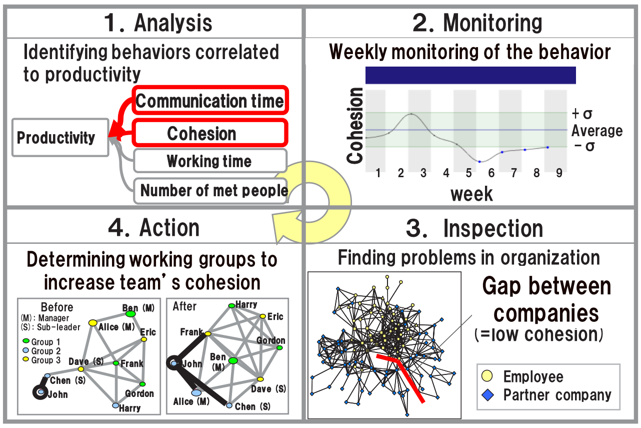


Fig. 8 Concept of four-step sensor-based project management process.

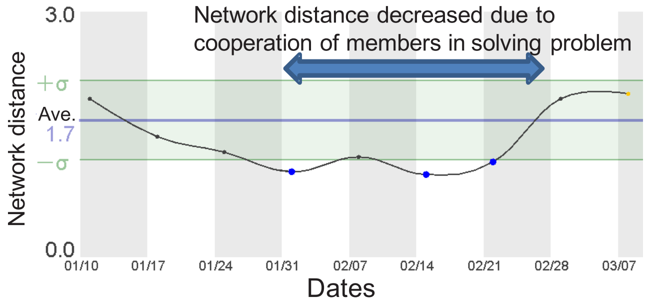


Fig. 9 Control chart of network distance between workers.

6.2 Monitoring

In light of the current problems in project monitoring, we have developed a behavior monitoring method for constant and quick monitoring of a project. Specifically, by monitoring the temporal transition of high-performance behavior, an unusual project is determined as having potential problems. One implementation involves using a control chart, as illustrated in **Fig. 9**. If something is regarded as irregular on the chart, senior managers are alerted when certain behavioral factors exceed thresholds such as one-sigma variation. Using this chart, a senior manager can quickly skim the status of each development group in a project and visit the group when he (or she) thinks it necessary.

This control chart is intended to fluctuate under problematic "unplanned" situations, such as changing specifications or problem solving, but it also fluctuates with regular "planned" events, such as project reviews or business trips. Even if an alert relates to a "planned" event, it does not cause a critical problem; it just takes up a little time for the manager. Notification of an "unplanned" event is more useful than that of a "planned" one. Given this fact, we investigated behaviors useful for detecting "unplanned" events.

We evaluated effectiveness of the monitoring method by using the data obtained in project 2. Since the concept of monitoring was proposed at the last moment of the sensor-data collection over the course of nine weeks, it was difficult to evaluate the real effect of behavior monitoring. Hence, the effectiveness of the proposed monitoring method was estimated by conducting interviews and investigating report logs after the sensor-data collection. In this study, we assumed that the control chart is updated weekly, considering current follow-up from the manager is conducted on a weekly basis. This update frequency can be optimized in a future study. It was also assumed that the system configuration generates an alert when the control chart fluctuates beyond certain thresholds (one sigma over or under the average) for two consecutive weeks. Under these configurations, 31% of the entire project fluctuated beyond the threshold, and 10% fluctuated over two consecutive weeks. For each simulated alert, each manager was asked to reflect on what happened in the target week in the project.

Table 6 Assumed monitoring signals.

#	Item	Detail
1	Amount of communication	Amount of communication averaged across team members
2	Number of employees communicated with	Number of employees communicated with for longer than three minutes
3	Amount of concentration	Amount of solo work with low activity level (below 2 Hz)
4	Network distance of leader and the other employees	Average path length between leader and each employee on network
5	Network distance of employees	Average path length between all pairs of employees on communication network
6	Cohesion	Density of network (clustering coefficient) weighted by number of employees connected (degree)
7	Amount of active communication	Amount of communication with high activity level (beyond 2 Hz).

Table 7 Summary of detectable events through control chart.

Category	Item	Number of alerts	Number of incidents
Planned	Absence	6	3
	Meeting	2	2
	Development	2	1
Unplanned	Absence	1	1
	Meeting	1	1
	Spec modification	6	3
	Problem solving	1	1
Unknown		2	1
	Total	21	13

Seven behavioral parameters (listed in **Table 6**) were chosen as monitoring signals. Indices 1 and 2 represent the "communication richness" factor described in the previous analysis, Index 3 is a key factor of development determined through interviews with senior managers, and Indices 4 to 7 indicate a common "agile organization" factor, which was determined from research on more than one hundred organizations [20]. "Active communication" refers to dialogue in an organization, "network distance" refers to communication up and down in an organizational chart, and "cohesion" represents the power of lower-level employees.

Through the investigation of the control chart of seven control signals for seven development groups in a project, 21 alerts were found to be generated over nine weeks. By analyzing each alert with the managers, 13 events were found to have occurred during this period, as summarized in **Table 7**. Specifically, half of the events were related to planned events, the other half were related to unplanned events, and one remains unknown.

Since the sample number was limited, it is necessary to keep collecting samples and investigating signals for detecting unplanned events. According to this evaluation, two hypotheses are put forward here:

(1) An unplanned event increases the number of employees communicating with each other.

(2) Time spent in solo work increases during a planned event, e.g., specification modification, while it decreases when solving an unplanned problem.

6.3 Inspection

As described in the previous subsection, irregular status of a project can be notified by control chart. In the next step, details of the irregularity and a potential problems should be investigated. Based on the analysis in Section 5, high performance behavior is supposed to be related with communication richness and workload. To help the inspection of such data, interactive display system "Hi-touch" was developed and located in the workplace (**Fig. 10**).

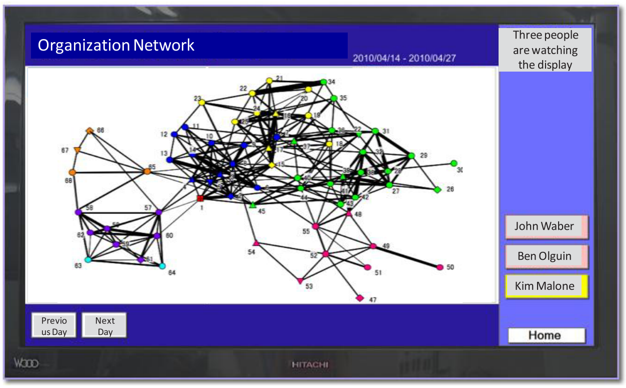
Fig. 10 Hi-touch Feedback display.

Two levels of feedback are made available. The first, team-level feedback, gives the status of a team summarized as a network diagram (**Fig. 11** (a)) and the transitions of specific indicators (Fig. 11 (b)). The team manager is quickly able to grasp the status of the team. The second, individual feedback, is provided as well for helping each employee (**Fig. 12**). Each employee knows who he (or she) communicated with and for how long. It is also possible to know how he (or she) used his (or her) time, namely, communication, solo work, or out of the office. Since these individualized data have a personal nature, they are provided only when the relevant employee is standing in front of the display. The presence of that employee is detected by a special device located near the display (**Fig. 13**).

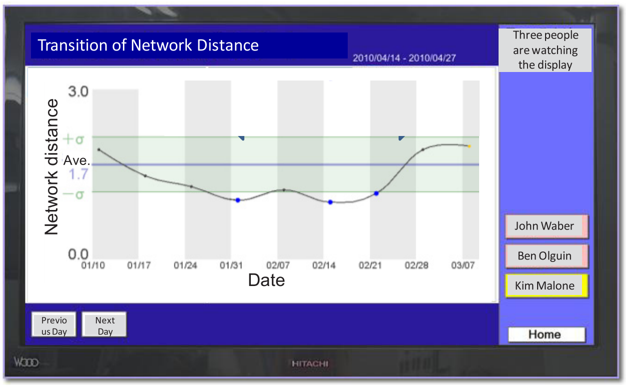
These team-level and individualized data used to be provided on the company website, but they are currently published through the display for two reasons.

- Employees do not frequently access the web when busy.
- When provided on the web, each employee used to look at the data alone; which resulted in he (or she) having few conversations about the data. However, once the data were published on the public display, employees started to analyze their data together, using their implicit knowledge. Behavioral data does not tell exactly what the organization and each employee is doing, what each employee said, or what job he or she is engaged in. However, it can reveal much information by combining an individual's memory and experiences.

The effectiveness of this system is evident from several viewpoints, such as increased user's frequency of viewing the display



(a) Network



(b) Transition of behavioral indicator

Fig. 11 Team view.

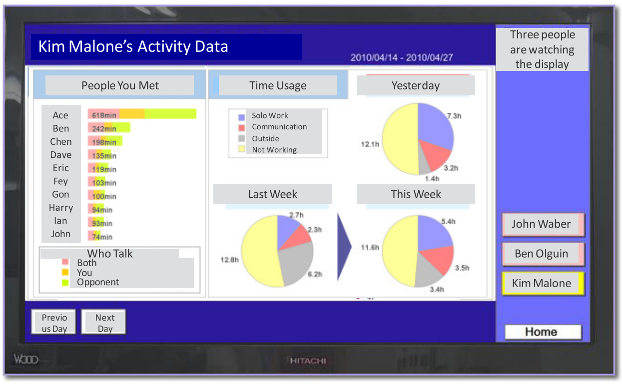
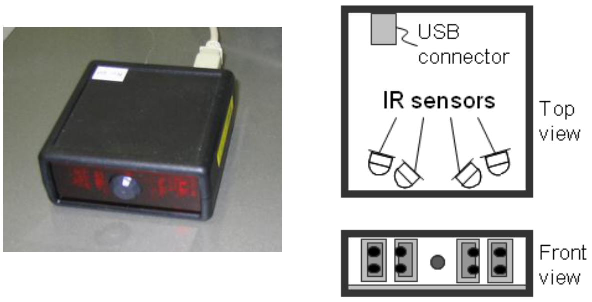
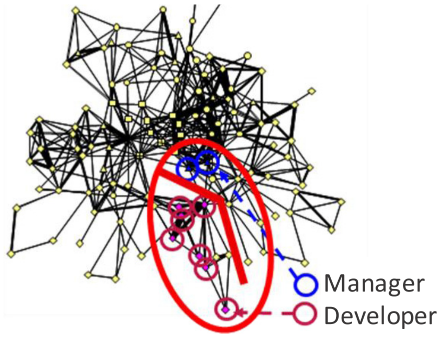


Fig. 12 Individual view.

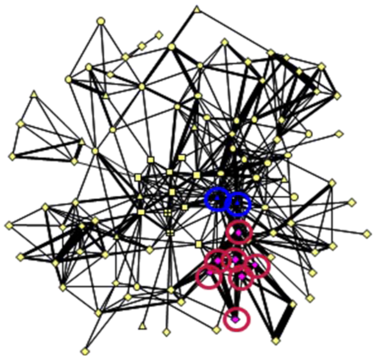


(a) Appearance (b) Inner structure

Fig. 13 Viewer detector.



(a) Network before WorkX was applied



(b) Network after WorkX was applied

Fig. 14 Network of software-development company. WorkX was applied to circled employees. Communication between managers and developers increased.

and increased individual employee satisfaction, but it still needs to be quantitatively evaluated.

6.4 Action

We provide more intensive and goal-oriented opportunities for employees by proposing short-term, micro rotation of team members through a display system called "WorkX." That is to say, to solve a problem by combining knowledge across employees, team members are assigned to discussions in accordance with the latest network topology of the organization and high-performance behavior detected in the previous analysis. For instance, in target project 1, members were selected so that the cohesion of the network would be maximized. In most companies, an employee's task is assigned by a manager. Each team also has an assigned task. When a team task is clear and can be divided into individual tasks, the work of both the manager and individual is simplified. In an actual situation, however, various uncertainties exist. Each employee has to communicate with others, even over the organizational silo, for finding solutions or obtaining support. The WorkX system automatically and continuously provides opportunities to look back at one's communication, solve problems, and create ideas.

To evaluate WorkX, which involves continuously rotating team members, it was introduced into a group of nine members assigned to develop difficult software modules, but a communication gap existed between managers and developers (**Fig. 14** (a)). The manager of the group agreed to try WorkX to clarify problems in the early phase of the project.

The WorkX system was configured to assign members to three

Table 8 Summary of change by applying WorkX.

		WorkX participants (N=9)	Other employees (N=114)
(a)	Before WorkX		
(1)	Degree	9.00	6.51
(2)	Clustering coefficient	0.64	0.48
(3)	Cohesion (1)*(2)	5.42	3.91
(b)	During WorkX		
(1)	Degree	11.78	4.91
(2)	Clustering coefficient	0.61	0.36
(3)	Cohesion (1)*(2)	7.04	3.14
(c)	Difference (b)-(a)		
(1)	Degree	2.78	-1.60
(2)	Clustering coefficient	-0.04	-0.12
(3)	Cohesion (1)*(2)	1.62	-0.77

teams, three members in each team, once a week. Each employee participated in two meetings per week, once with assigned group and once with all members, for sharing information. In the first couple of discussions, developers seemed hesitant to express their opinions because they were given no chance to do so previously. The managers, however, repeatedly asked for their opinions in a positive atmosphere over the course of a four-week trial, and the developers got used to giving their opinions. One opinion was that several developers need an opportunity to ask managers questions. This might seem like a basic requirement, but in the group, no process had been established. At the end of the trial periods, the managers improved the communication processes by incorporating a time for questions in every meeting. Most developers mentioned that this process is very useful for their job and comfortable enough to maintain.

Sensor data can ensure that an intended change is actually implemented. By continuously enhancing communication within a team, the communication gap between the managers and the developers was eliminated, as shown in Fig. 14 (b). Changes in communication data, such as degree and cohesion, also provided a clue to behavioral change, as depicted in **Table 8**.

7. Summary

We applied a wearable sensing system to a software-development project and analyzed the relation between employees' performance and behavior. In the past, managers intuitively knew the importance of communication through their own experience; however, we quantitatively found that the amount of communication is a key factor for both managers and developers. A four-step sensor-based project management process was proposed as a result of this analysis. The monitoring display was able to identify some "unplanned" events, and short-term, micro rotating of discussion members systematically increased cohesion of a network. Additional research is needed to shed light on agile and large-scale project management.

As described, we primarily focused on systems for software project management because measuring performance is straightforward and the systematic monitoring process is already incorporated in the management structure. For instance, it is more difficult to measure performance in non-routine work, such as in a research group or design group. Once the system is established, however, our focus can be broadened to the other routine work, such as in hospitals or call centers, in the next step.

Further research is required in real and emergent situations. Once our proposed management process is incorporated into a company, employees may potentially hide or even fake their behavior to avoid taking responsibility of a problem. In such a situation, information disclosure should be optimized by anonymizing personal information or by controlling the ownership of information.

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