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Remote-Collaboration System Using Mobile Robot with Camera and Projector

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***Abstract* - We have been studying a remote-collaboration system called SCOPE (sight collaboration by projection effect) featuring image projecting and capturing capabilities as implemented in a maintenance robot. With the help of SCOPE and a remote support person, an on-site worker can perform maintenance very efficiently. We propose a mobile SCOPE that can significantly expand the area of activity of the conventional SCOPE. To enable an on-site worker to share the field of view of a remote support person, we developed a technique for aligning the optical axes of a camera and a projector. We present experimental data that demonstrates the validity of our optomechanical design. Finally, we show that the mobile SCOPE enables workers to continuously share their field of view, no matter where the mobile SCOPE moves.**

Index Terms - Remote collaboration, Shared field of view, Mobile robot, Camera and projector, Tele-operation.

I. INTRODUCTION

To create a more efficient environment in which to perform remote maintenance over a network, we have been studying a new collaboration concept, called "robot-augmented communication" (RAC) [11]. In RAC, a maintenance robot and an on-site human worker, who may not be skilled in maintaining the target object, are assisted by a veteran operator of the object at a remote support center. RAC provides effective support for on-site workers by augmenting the communication ability of the remote support person with robotic functions that people do not have.

A prototype remote-collaboration system called SCOPE (sight collaboration by projection effect) was developed as a maintenance robot that was the first instance of RAC, which featured image projecting and capturing capability. This SCOPE system, equipped with a projector and a camera, enables a target object perceived in the field of view of a remote support person to be shared with an on-site worker. This function should dramatically shorten the time taken to perform maintenance operations.

However, this SCOPE system cannot move about in an on-site maintenance area. Generally, on-site maintenance areas include very large plant sites or huge industrial facilities, so mobility is indispensable. Therefore, we present a mobile SCOPE and discuss its key technological issues. A future scene of remote support using the mobile SCOPE is shown in Fig. 1. As far as we know, such a robotic system has never been reported before.

Numerous papers on real-space projection technology utilizing a camera and projector set have been published, mainly in the fields of augmented reality (AR), Computer Supported Cooperative Work (CSCW), and ubiquitous computing [1]-[5]. Almost all of these studies focused on applications inside a room in an office or home, so the equipment was spatially fixed to the room structure such as to a desk, ceiling, wall, or floor. Utilizing a head-mounted display [6] or hand-held projector [7] enables us to move about in an on-site maintenance area; however, the current size and weight of such devices make them too troublesome to wear and carry around. In that respect, mobile SCOPE can relieve the on-site worker from having to wear such heavy, bulky devices.

On the other hand, the addition of mobility to the SCOPE system will cause an inherent, serious problem with sharing the field of view in an actual space because the spatial relationship between the image frame of the camera and that of the projector will change depending on the distance between SCOPE and the target to be captured and projected. Therefore, one of the most important problems for a mobile SCOPE is to maintain a shared field of view, no matter where the SCOPE system moves. To overcome this problem, we describe a method, based on the use of an ingenious optomechanical structure, that enables the optical axis of the camera and that of the projector to be aligned.

After a brief introduction of our RAC concept and the

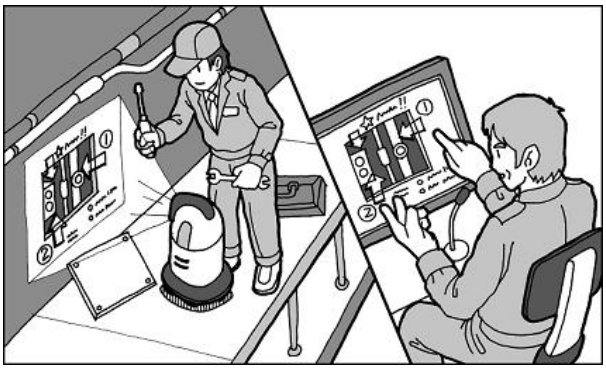

Fig. 1 Future scene of remote support using mobile SCOPE

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conventional SCOPE, we discuss requirements for the mobile SCOPE and its key technology for optical-axis alignment of the camera and the projector. Next, we provide experimental data on the evaluation of the optomechanical design of the mobile SCOPE. Finally, we describe implementing the mobile SCOPE with an optomechanical design that enables an on-site worker to share the field of view of a remote support person, no matter where the SCOPE moves.

II. Concept for New Collaboration between Robot and Human over Network

A. *Robot-Augmented Communication*

When no skilled workers are present at a work site, there are two ways of handling maintenance: either remotely operate a robot and devices at the site [8] [9] (see Fig. 2(a) below) or dispatch an unskilled worker to the site and remotely instruct him/her to perform maintenance operations from a distance [6] [10] (see Fig. 2(b)). In Fig. 2(a), a robot that interacts with a maintenance object cooperates with and is controlled by a remote, skilled operator through a network. In Fig. 2(b), an unskilled worker and a skilled operator cooperate through a network, and the unskilled worker interacts with the maintenance object. Each of these two cases – namely, the robot or the person handling the on-site operation – has its advantages and disadvantages, as explained below.

(a) Remote-controlled robot: Robot function, e.g., in terms of power and information-processing capability, can surpass that of a human operator, but the current level of robot autonomy is low and cannot match the operation skill of a remote skilled worker.

(b) Remote-supported human: Generally, the decision-making capability of a person in response to site conditions is much better than that of a robot. However, sufficiently conveying the intentions of the remote support person, i.e., skilled operators, without putting undue stress on the unskilled worker is difficult under the present state of communication between unskilled on-site workers and skilled remote support workers. For example, due to the time delay of a network, the supporter's intention often cannot be transmitted rapidly and easily.

With the drawbacks of the above two approaches in mind and aiming at extending the skill and ideas of a remote support person to cover work sites, where specialized robotic functions such as high-level information processing are particularly applicable, we propose a new form of collaboration between robots and on-site workers who have high decision-making capability. We have extended communication by means of a robot's functions, so this collaboration setup is called "robot-augmented communication" (RAC). As shown in Fig. 2(c), RAC provides effective support by emphasizing the intentions of the remote support person through the robot. This is achieved by actively utilizing the interaction between an on-site worker and robot functions that cannot be performed by humans.

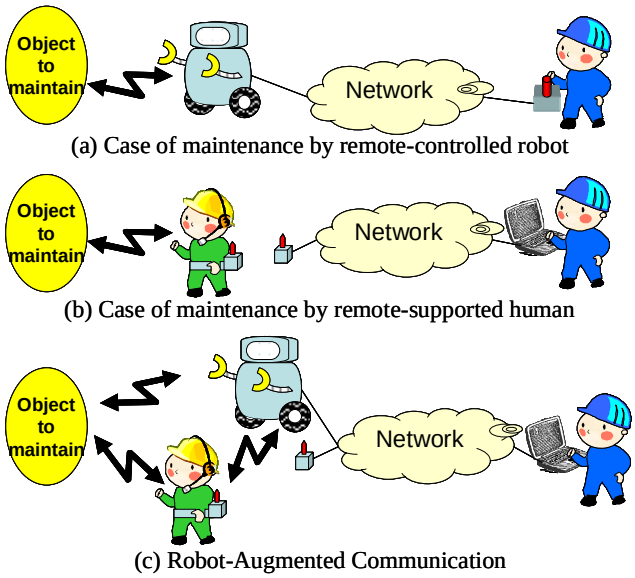

Fig. 2 Setups for remote maintenance.

B. *SCOPE: System for supporting a shared field of view in an actual space*

We selected the function of projecting information in an actual space as a robot function that is intended to surpass the ability of humans. In this section, we introduce a remote-support system called SCOPE as the first instance of an RAC concept.

1) *System overview*

A schematic of the configuration of this system is shown in Fig. 3. At the on-site worker's location, a camera and a projector are integrated in one piece, and an incorporated stepping motor enables the camera's viewing field and projected images to rotate around the vertical axis of a camera and projector unit. To attain the capability of a "shared viewing field" as explained later, domains of the viewing field of the camera and that of the projector are adjusted so that they are aligned. An on-site worker can use a laser pointer as an input interface. We implemented a manipulation function

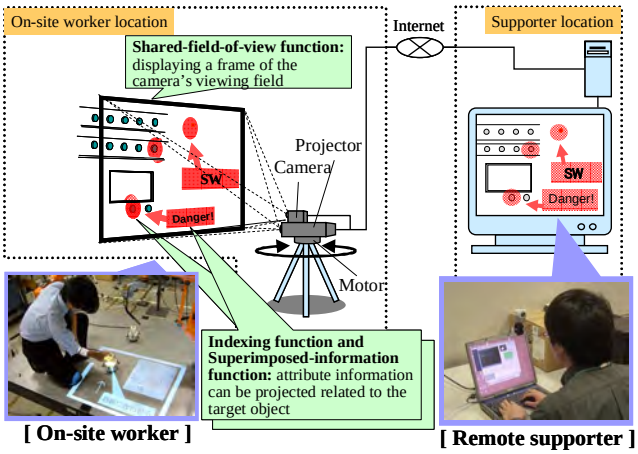

Fig. 3 SCOPE system.

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equivalent to the mouse on the client PC by applying image-recognition processing at the position of the laser pointer's spot.

2) Shared-field-of-view function

During collaborative operations at remote locations, a situation that often occurs is a remote support person verbally indicating relative directions like "on the right" to give instructions to an on-site worker. At such times, the remote support person's viewing field becomes essential information from the viewpoint of the on-site worker. In the SCOPE system, presenting the remote support person's viewing field to the on-site worker is possible by unifying the camera's viewing field and projector's projection area and displaying a frame of the camera's viewing field on the projected images.

3) Indexing function

Information needed for carrying out operations, "attribute information," is projected onto the target object as the occasion demands. This is like affixing notes on the target object with light. In the developed system, five kinds of information are conveyed: text, still images, video, sound, and program administration. The location of attributed information is indicated as a graphical image with a circular form. We call this mark a "projected image". By manipulating a projected image, one can also manipulate the display status of attribute information. At the on-site worker's location, the laser pointer is used to manipulate the projected image. At the supporter's location, the projected image is shown on a communication screen, which displays images transmitted from the on-site worker's location, and manipulated using the PC's mouse.

4) Superimposed-information function

In the SCOPE system, the camera/projector unit at the on-site worker's location can be manipulated from the supporter's location. The projected image and the attribute information are positioned on the target object by correcting the position of a projected image according to the movement of the camera and projector unit. This function enables the on-site worker to intuitively recognize the relationship between a stationary object in space and its attribute information.

5) Effectiveness of SCOPE for maintenance

The effectiveness of SCOPE was evaluated by experiments on two types of fundamental tasks, "comprehending the target object" and "transmitting instructions", involved in a typical maintenance operation. The experimental results indicate that shared-field-of-view, indexing, and superimposed-information functions are effective in shortening the time taken to perform the maintenance operation.

III. Hardware Design For a Mobile-type SCOPE

In this section, we discuss the hardware design of the mobile SCOPE in terms of user requirements and the conventional SCOPE technology. We use a planar mobile robot on which a camera-projector pair is mounted.

A. Requirements for utilizing SCOPE in an actual space

First, we assumed a very wide area with a flat floor in a huge indoor plant as the working environment of the mobile SCOPE. Therefore, we used a robot that has wheels with two degrees of freedom (DOF) of planar mobility. These DOF should be necessary for traveling in a wide working area and for avoiding projections, which are occluded by the on-site worker's body, between the robot and the object to be maintained.

B. Setup of projector and camera

We considered a projection plane approximately 4 × 4 m, about 1 – 3 m away from the mobile robot. A single small fixed projector cannot cover such a wide area, so pan-and-tilt rotational DOF are indispensable to broaden the projection coverage. On the other hand, rotation with respect to the optical axis is not needed because an on-site worker mainly works in a vertical standing position. We do not have to actively control the three translational DOF of the projector (one vertical and two horizontal) because we can relatively easily modify a projection image that has trapezoidal distortion caused by slanted projection on a flat plane. Based on the above discussion, we eventually designed a two-rotational-DOF projector on a 2-DOF planar mobile robot on wheels.

Many research studies have been performed on the autonomy of a mobile robot. For example, autonomous navigation technology such as path planning or SLAM (Simultaneous Localisation and Mapping) is a crucial issue that needs to be resolved for mobile robots. However, in the RAC concept, the present low level of mobile robot capabilities can be supplemented by human capabilities. On the other hand, the shared-field-of-view function of the mobile SCOPE has a fatal problem, as discussed in detail in the next section.

IV. Optomechanical Design

In this section, we discuss the layout for mounting a projector and camera on the mobile robot. First, we explain why aligning the optical axis of the projector and that of the camera is important, and we describe the optomechanical design for achieving this.

A. Issues in sharing field-of-view function of the mobile SCOPE

The basic functions of our mobile SCOPE include the following.

(1) Showing the remote support person's field of view by projecting the image frame of the camera

(2) Projecting various information on the viewing field as a shared area

(3) Enabling functions (1) and (2) in any place

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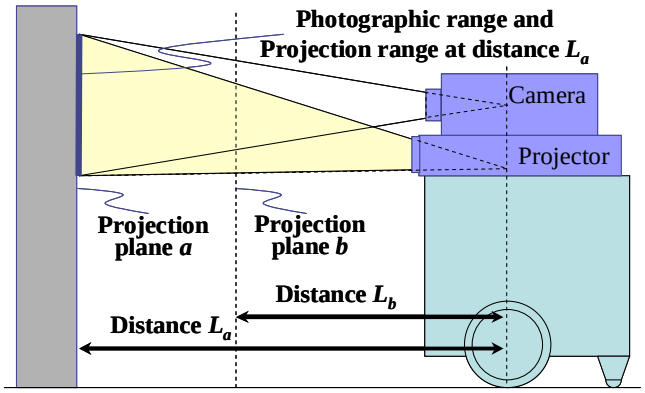


Fig. 4 Relationship between distance to projection plane, and photographic and projection ranges.

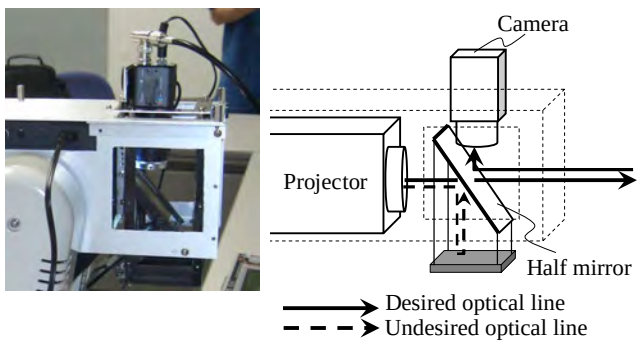


Fig. 5 Setup for aligning optical axes with half mirror.

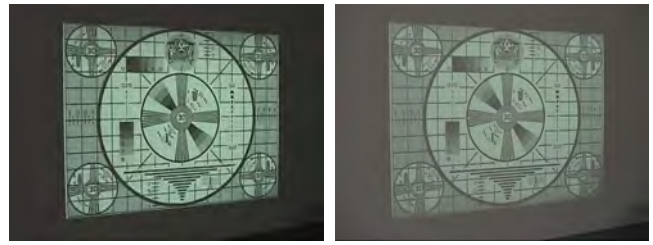
For the conventional SCOPE, we confirmed (1) and (2) by simply assembling the camera and projector so that their frames correctly overlapped on the projection plane. In this configuration, if the distance to the photographic plane (or the projection plane) is fixed, adjusting the orientations of the camera and projector only once is sufficient, which makes installation relatively easy. In the mobile SCOPE case, however, the distance is not fixed.

As shown in Fig. 4, if the camera's photographic range and the projector's projection range are the same at a projection plane located at distance L_a, then the photographic and projection ranges are not the same in projection plane *b* for distance L_b. To deal with this problem, one might normally have to develop one of the following.

(i) A hardware mechanism for automatically correcting the orientations of the camera and projector

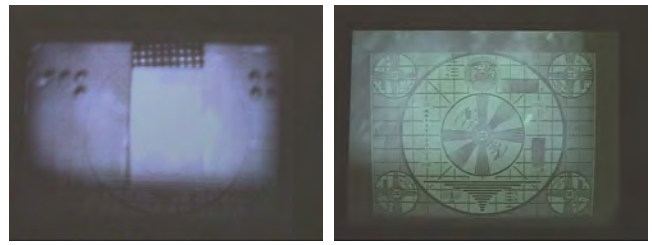
(ii) A real-time image-data-processing method that maintains the projected content within the visual field of the camera.

These are both very difficult and laborious to implement. Therefore, we propose another novel approach utilizing a half mirror.



(a) Directly projected image (b) Projected image through half-mirror

Fig. 6 Projected images on projection plane.



(a) Without black flock paper (b) With black flock paper

Fig. 7 Images captured by camera on SCOPE.

B. *Aligning optical axes with a half mirror*

To match the photographic range of the camera and the projection range of the projector independently of the distance to the subject, the ideal situation is for the focal point of the camera and the light source of the projector to be the same. However, this is impossible due to hardware restrictions. Therefore, we chose to achieve the same function by using a half mirror. First, as a preliminary investigation, we conducted an experiment using the equipment illustrated in Fig. 5.

Projected images on a projection plane without and with a half mirror, where the rate of reflection with respect to the rate of transmission, R:T, is 3:7, are shown in Figs. 6(a) and 6(b), respectively. The luminance of the projector is 1,500 lumens. These photographs were taken by another camera; they are images of what the on-site worker can see with the naked eye. Naturally, Fig. 6(b) is darker than Fig. 6(a).

Images captured by a camera on the mobile SCOPE are shown in Figs. 7(a) and (b). These are images of what the remote support person can see through the mobile SCOPE. If these images are completely the same as those in Fig. 6(b), the remote support person can see exactly what the on-site worker sees. However, they are clearly different, as is seen by comparing Figs. 6 and 7. In particular, Fig. 7(a) is extremely poor. An image of the black chassis passing through the half mirror is shown instead of the desired image. We call this phenomenon 'ghosting'. Ghosting occurs when the projector light that is reflected in the direction of the chassis is too bright. To delete the ghost image, we tried placing black flock paper on the chassis, and an image of that is shown in Fig. 7(b). The black flock paper reduces the ghosting. However, excess light still appeared in the camera image. The next section describes a method to eliminate this excess light.

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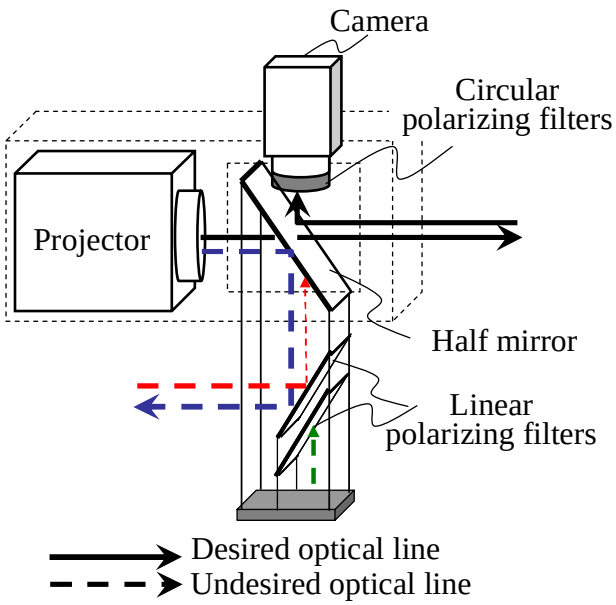
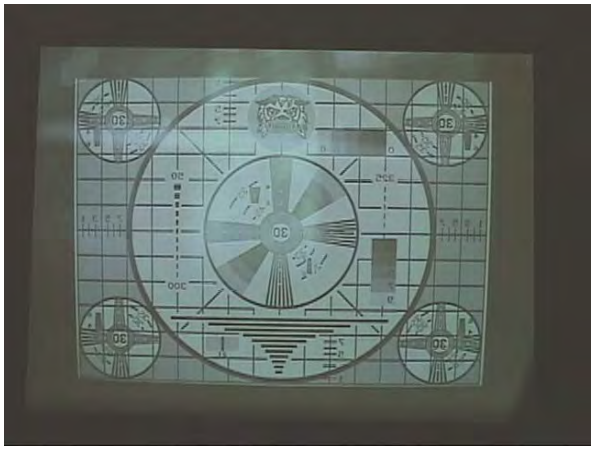
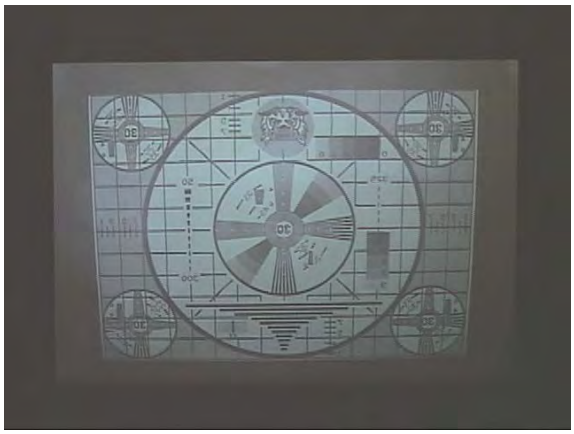


Fig. 8 Construction to eliminate ghost image.



(a) With linear polarizing filters



(b) With linear and circular filters

Fig. 9 Images captured by camera on SCOPE with polarizing filters.

C. Polarizing filters to eliminate the ghost image

We investigated ways to eliminate the excess light that passes through the half mirror and appears in the camera image. Utilizing polarizing filters is the key to solving this problem. The most effective configuration for eliminating the excess light is shown in Fig. 8. In this configuration, two linear polarizing filters reflect ambient light in the direction of the half mirror, and the circular polarizing filter blocks the light that has passed through the half mirror.

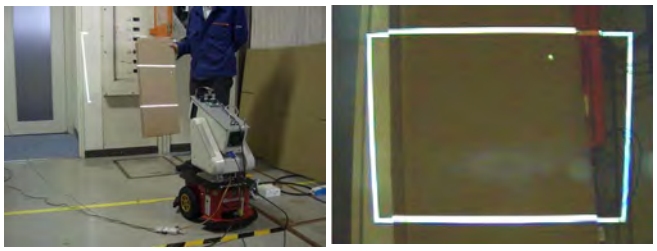
Images captured by the camera mounted on the SCOPE are shown in Fig. 9. They demonstrate the effectiveness of using polarizing filters. The result obtained when two linear polarizing filters were used is shown in Fig. 9(a). As the figure indicates, background image noise was cut by the linear polarization filters, compared with that of Fig. 7(b). However, the excess light that was reflected at the linear polarization filter and passed through the half mirror still appeared. The result obtained when two linear polarizing filters and a circular filter were used is shown in Fig. 9(b). The excess light from outside, which was present in Fig. 9(a), is reduced. This camera image can convey sufficient information about the on-site worker's site to a remote support person.

Photographs taken from the on-site worker's viewpoint and from the supporter's viewpoint, are shown in Figs. 10(a) and (b), respectively. Although the on-site worker's rectangular frame is extremely deformed by nonflat planes that consist of a cardboard and the background, the supporter's rectangular frame is almost the same as the rectangular frame of the projected image. This is evidence of the alignment of the optical axes of the camera and the projector.

From these experimental results, we confirmed the validity of our idea of using a half mirror and polarizing filters.

D. Implementation of mobile SCOPE

We unified a projector and a camera in the manner shown in Fig. 8 and mounted them on a mobile robot, Pioneer 3 manufactured by Active Media. A scene of remote support using the mobile SCOPE is shown in Figs. 11 and 12. Clearly, the viewing field of the remote supporter can be displayed in the on-site space. Aligning the optical axes enables sharing the field of view no matter where the mobile SCOPE moves. In this case, the position and orientation of the mobile SCOPE is controlled by the remote support person to find a target object or to avoid obstacles. Furthermore, the indexing and superimposed-information functions of the conventional



(a) On-site worker's viewpoint (b) Supporter's view point

Fig. 10 Result of aligning optical axes.

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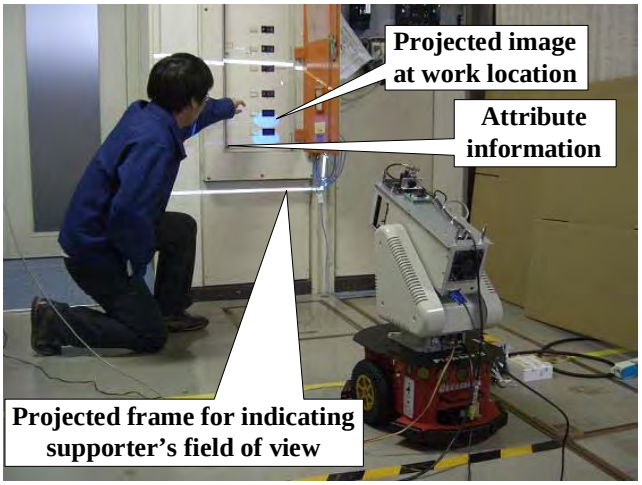


Fig. 11 Mobile SCOPE (on-site location).

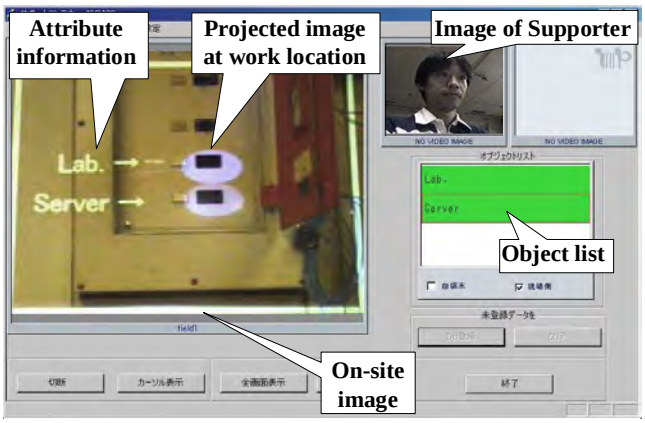


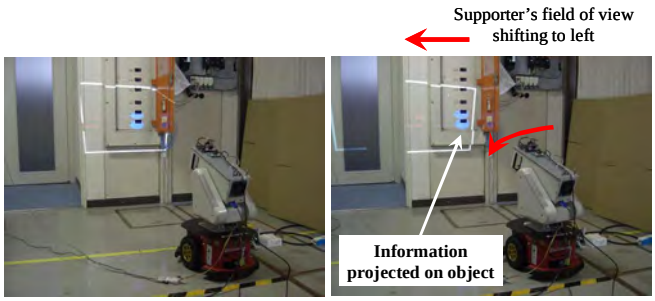
Fig. 12 Screen shot (supporter's location).

SCOPE were also implemented. Two photos indicate the result of automatic correction of the position of projected attribute information, as shown in Figs. 13(a) and (b).

V. Conclusion

To create a more efficient environment in which to perform remote maintenance over a network, we proposed a mobile SCOPE to significantly expand the field of activity. We developed a technique for aligning the optical axes of the camera and the projector to share the field of view between an on-site worker and a remote support person. Experimental data regarding the optomechanical design demonstrated the validity of our idea.

A conventional technique of many optomechanical systems uses a half mirror, such as that in a see-through head-mounted display. However, those systems are not relevant to the problems discussed in this paper such as "ghosting" because they do not use a bright light source like a projector.



(a) Start position (b) After left rotation

Fig. 13 Result of automatic correction of projected attribute information.

Therefore, a major contribution of this paper is the new finding of a new interdisciplinary research field covering AR and robotics. We plan to extend the autonomy functions of the mobile SCOPE to include obstacle avoidance or tracking target objects.

Acknowledgement

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