Development of an Ergonomic Control Panel Layout System and its Application

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ABSTRACT

A control panel layout system was developed to generate an ergonomically sound panel design. A constraint satisfaction concept was introduced as a framework of incorporating diverse ergonomic design guidelines into the panel layout. An efficient search algorithm which can find a constraint satisfaction solution within a reasonable time was developed based on preprocess and look_ahead procedures with the backjumping technique. The prototype panel layout system was developed on a SPARC workstation. The constraint satisfaction algorithm was programmed in C language with Motif as a GUI tool under the X-windows environment. The effectiveness of the prototype panel layout system was examined by a case study.

1. Introduction

In industry, ergonomically sound control panel design becomes increasingly important as more displays and controls are left to be managed by operators in the modern manufacturing environment. The manufacturing processes are getting more centralized and the controls of modern facilities are becoming far from a simple series of operations. On the other hand, the management strives to keep the personnel administration to be lean and slim without operator's workload being properly evaluated.

The primary goal of the research is to develop an ergonomic panel layout system in which displays and controls are properly arranged with sufficiently reflecting the ergonomic guidelines and other domain-specific knowledge. The effectiveness of a developed panel layout system will be evaluated through a case study.

2. Preferred Areas for Critical Instruments

To realize the ergonomic principles in the layout, the designer can determine the areas for the critical instruments. An adequate area for displays and controls is chosen by the designer before starting search procedure. For displays, the designer can select one of three visual areas such as preferred area, eye field, and head field (Sanders, 1970). The smaller the area is defined, the closer the critical instruments come to the center of a panel. However, it may yield an infeasible solution if too small visual area is selected. The selection of the preferred visual area is related to the constraints relaxation for resolving the conflict between the constraints.

For controls, also three levels of comfortable working area are provided to the designer. Based on the isocomfort working area (Jung et al., 1995a), "so-so" level as the most broad preferred working area, "good" level as the smallest area, and "good a little" level as the intermediate area were implemented in this system. The designer can choose one among these areas from the edit mode of the preferred working area. Similarly with the preferred visual area, the determination of the working area is closely related to the constraint relaxation process.

Since the working comfort for control manipulation depends on the operator's percentile, the areas for female 5th percentile and for male 95th percentile are provided according to the designer's selection. The consideration of the percentile and the gender effect makes it possible to generate the layout suitable for a specific operator. The type of controls was also considered in the determination of the working area.

3. Constraint Satisfaction Algorithm

A panel layout design can be seen as a process of solving the two dimensional bin-packing problem under a set of constraints which reflect various design guidelines. Since a layout planning is a search process characterized by a vast amount of search space, the development of a search algorithm that eliminates in advance the unnecessary search space is essential (Baykan and Fox 1991). In this study, the concepts of "preprocess" and "look_ahead" were employed to cut down the search space and quickly find a solution satisfying the given constraints. And, a modified backtracking algorithm generally called backjumping was also employed to avoid meaningless search (Kumar, 1992).

3.1. Constraint Representation

Prior to applying constraint satisfaction algorithm to the panel layout problem, the formalization of design principles or constraints into an implementable format is indispensable. In this study, the concepts of S_{ij}, I_{ij}, D_{ij}, PV, and CW are introduced to formalize the constraints. S_{ij} was introduced to represent the relative position between instruments i and j. It indicates a set of possible positions of instrument j with respect to i (Jung et al, 1995b).

I_{ij} indicates the set of instruments allowed to be placed between instruments i and j. The null set means no instrument can be located between two instruments i and j. When I_{ij} is declared as null, the constraint is examined by checking whether or not any square block of other instruments intervenes between instruments i and j. The area where other instruments cannot be located is determined by the size of the small instrument when the size of two instruments are different. D_{ij} is the maximum distance between instruments i and j. The distance between two instruments is the number of unit square blocks between the facing borders of the instruments i and j. In addition, PV and CW represent the set of instruments which must be located within the preferred visual area and comfortable working area, respectively.

3.2. Preprocess Procedure

Since the search space for the layout design problem is usually too large to be searched without a technique carefully designed to reduce the search space, the procedure "preprocess" is a preparation step designed to prevent unnecessary search steps. Constraints play a major role in reducing search complexity. In this step, the region where each instrument can not be located is excluded from the search space by applying the constraints that restrict the location of instruments.

Another useful advantage of the preprocessing is that the designer can obtain the information about the feasibility of the problem before the search procedure. If no feasible region for a certain instrument is obtained by preprocess procedure, the search procedure will fail to find a solution after all. Since the relative positions and the absolute positions of each instrument are examined in advance by the preprocess procedure, most cases of infeasible solutions are detected in this stage.

3.3. Look_ahead Procedure

The look_ahead scheme guides the decision of what variables to instantiate or what values to assign among all possible choices. In this study, the look_ahead procedure consists of two ordering schemes, namely, variable ordering and value ordering. In the case of a panel layout, the coordinates of the instruments correspond to variables, and the possible positions of instruments are values. That is, the variable ordering determines the sequence in which the instruments are located, and the value ordering decides what position to consider first. A good ordering scheme reduces the number of backtracking, and thus, leads to a quick solution. The look_ahead procedure reduces the search effort while the preprocess procedure does the search space.

4. A Resolution Procedure for Constraint Conflicts

One of distinct characteristics of the proposed layout system is that the system is capable of treating multiple layout criteria concurrently. When multiple constraints are considered, some constraints may be in conflict with each other. If the problem has substantial conflicts of constraints, the search procedure repeats the backtracking and verifies that the solution space is infeasible after all. Unfortunately, the designer can hardly know which constraint will yield a conflict when the search fails to find a solution. The arrangement order of the instruments, variable ordering, can be effectively used to detect where in the search process a conflict occurred.

The current depth on the search tree is displayed in the screen during the search process so that the designer is able to obtain the information about the instrument which cannot find a proper location. By simply matching the current depth information to the instrument order information, the designer can find out what instruments concerns with the incompatibility of constraints, and thus, can take proper corrective actions for the conflict resolution. The conflicts between constraints can be resolved by several rules of thumb. Three relaxation methods all of which are based on the interactions with the designer are suggested as guidelines for the conflict resolution.

First. *Determine broader preferred areas.*

This recommendation is suitable for the case that too many instruments or too large instruments need to be located in the preferred visual area or the comfortable working area. For example, if the current comfortable working area was determined based on "good" working comfort, the choice of the comfort level such as "good a little" or "so-so" can have more controls located in the relaxed comfortable working area.

Second. *Relax the value of the constraint variables.*

It means the modification of an assigned value for the constraint variable such as S_{ij} and D_{ij}. The constraint such as "the instrument B should be located above the instrument A" can be either formalized to $S_{AB}= \{1\}$ as strictly, or $S_{AB}= \{1,2,8\}$ as loosely. It is apparent that the latter broadens potential locations for those instruments than the former. The maximum permissible distance, D_{ij}, can be relaxed in a similar manner. The increase of D_{ij} value may also provide the expanded feasible region of instruments i and j.

Third. *Remove the less important constraints.*

This resolving scheme is the most direct, but simple approach. If a constraint caused any incompatibility with other constraints can be regarded as less essential, the constraint can be removed from the constraints set. The evaluation of importance is, of course, based on the designer's discretion. Once a solution is found by this resolution method, it is encouraged that the removed constraint in a relaxed form enters the solution-finding process again.

It should be understood that there is no "best" way to resolve the conflicts. Different designers may adopt different resolving methods. The appropriateness of a selected resolving scheme is thought to be highly problem specific. The next section describes an illustrative example that a satisfactory solution is generated and iteratively improved by the interactive resolution approach.

5. Development of a Panel Layout System

The prototype panel layout system was developed on a SPARC workstation (SUN Microsystems, Inc.), in which Motif was used as a GUI tool. The constraint satisfaction algorithm was programmed in UNIX C language under the X-windows environment. The overall structure is presented in Figure 1.

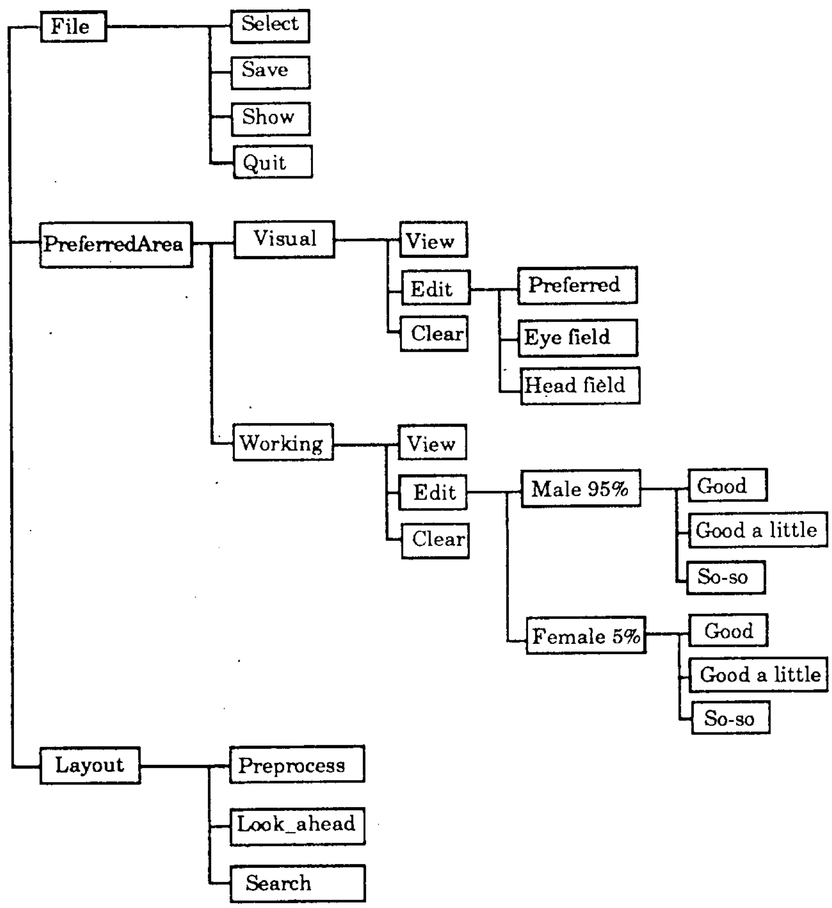

Figure 1. The structure of the prototype system

6. A Case Study

6.1. Problem Descriptions

The applicability of the developed layout system was evaluated through a case study of redesigning the control rooms in the cold rolling plant of the P steel company. At present, the management plans to renovate two existing control rooms, a pickling and cold mill (PCM) control room and a sidetrimmer control room, and also to integrate them into a combined control room to improve efficiency. When the integration is successfully achieved, a considerable improvement of the productivity as well as reduction of workers is anticipated. However, such an integration may cause operator's overload if it is done without the proper consideration of the operator's workload.

In addition, the integration will inevitably bring the reduction of the room size due to the physical constraints of the plant. Accordingly, all displays and controls ought to be densely placed on control panels. It means that the efficiency of the monitoring task will be heavily dependent on the configuration of the instruments. Therefore, it is strongly requested to design an efficient panel layout that maximizes the task performance.

6.2. Task Analysis and Redesign

Among the five control panels in the PCM monitoring room located in the entrance side, the main control panel, DEP02, for the coiling and welding task was chosen for the redesign of the existing layout configuration through the system. This panel is composed of 62 instruments, 17 displays and 45 controls. The types of displays used in this control panel are as follows: two monitors (A, B), three circular analog displays (C, D, E), five button lamps (F, G, H, I, J), five digital displays (K, L, M, N, O), and two indicators (P, Q). And, three types of controls are used such as 12 hand levers (1 through 12), 21 select buttons (13 through 33), and 12 push buttons (34 through 45).

From the results of a prior task analysis, the most frequently used instruments are the monitor, A, the circular analog display, D, the button lamp, G, and the push buttons, 42, 43, 44, and 45. On the contrary, it was found that the displays K, H, M, N, O, and P, and the controls 1, 2, 3, 6, 7, 8, 13, 14, 15, 16, 18, 20, and 21 are rarely used for the task. And, the controls 22, 23, 24, 25, 26, and 27 are used only for initially setting the process operations. The critical instruments for performing the task are the monitor A, the circular analog display, D, the button lamp, G, the push buttons, 34, 35, 40, and 41. These facts were used to determine the instruments which should be located in the preferred visual area and working area.

The instruments C and G are used for monitoring the position of a loop Car 3, and the controls 2 and 15, and 3 and 16 are utilized for knife gap adjustment and knife wrap adjustment in a sidetrimmer operation, respectively. The four hand levers, 6, 7, 8, and 10 and the two select buttons, 29 and 33 are the controls for tension leveling operation, more specifically, 10, 29, and 33 for the preparation operation and 6, 7, and 8 for the adjustment of a tension leveler. Consequently, these instruments should be arranged in groups according to the task type performed. Furthermore, the following displays and controls such as (H-1), (I-19), (J-5), (M-6), (N-7), and (O-8) are the corresponding pairs. It means that these instruments must be located while keeping the spatial compatibility.

The operation flow analysis indicates that the select buttons, 13, 15, and 16 are sequentially operated in sidetrimming composed of knife selection, knife gap adjustment, and finally knife wrap adjustment. The controls 2 and 3 are also successively operated in the order of knife gap and knife wrap adjustment. The displays O, N, and M, and the controls 8, 7, and 6 are related to the adjustment of a tension leveler in sequence. The button 30 is used for starting the air jet machine, and the button 28 is manipulated for the air jet adjustment. Therefore, these instruments should be arranged based on their operational sequence, and no other instrument must be located between these instruments for smooth operation.

In order to meet such requirements obtained from the task analysis, the prototype layout system was applied to find a satisfactory solution. The generated solution from the prototype layout system appeared in Figure 2. It took about ten minutes on a SPARC workstation to generate a solution. Because all the operators working in the control room were males, the comfort level of preferred working area was selected as "good for male". The preferred area was selected as the visual area to guarantee the best visual performance.

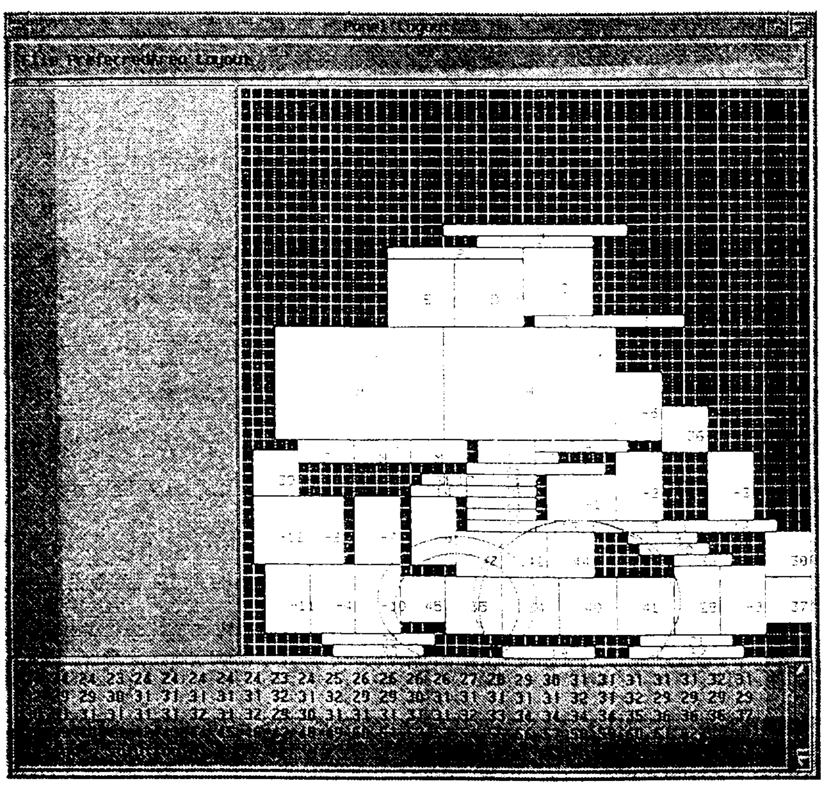

Figure 2. A layout solution for DEP02 panel by the prototype system

6.3. A Comparison with the Current Layout

Figures 3 and 4 show the current layout of DEP02 and the new layout design from the panel layout system, respectively. The current layout of the DEP02 panel can be said to be very poorly designed from the ergonomic viewpoint. As seen in Figure 3, the displays A, D, and G, and the controls 42, 43, 44, and 45 were located at the outer region of the panel although these instruments are most frequently used to perform the necessary tasks. On the contrary, the display P, and the controls 18, 20, and 21 which are rarely used instruments were arranged around the center of panel. Furthermore, the controls 22 through 27 were also located around the center of the panel while these are used only for the setting task which occurs at most two or three times a week. This is mainly due to the fact that task analyses or ergonomic considerations had not been properly taken when it was originally installed.

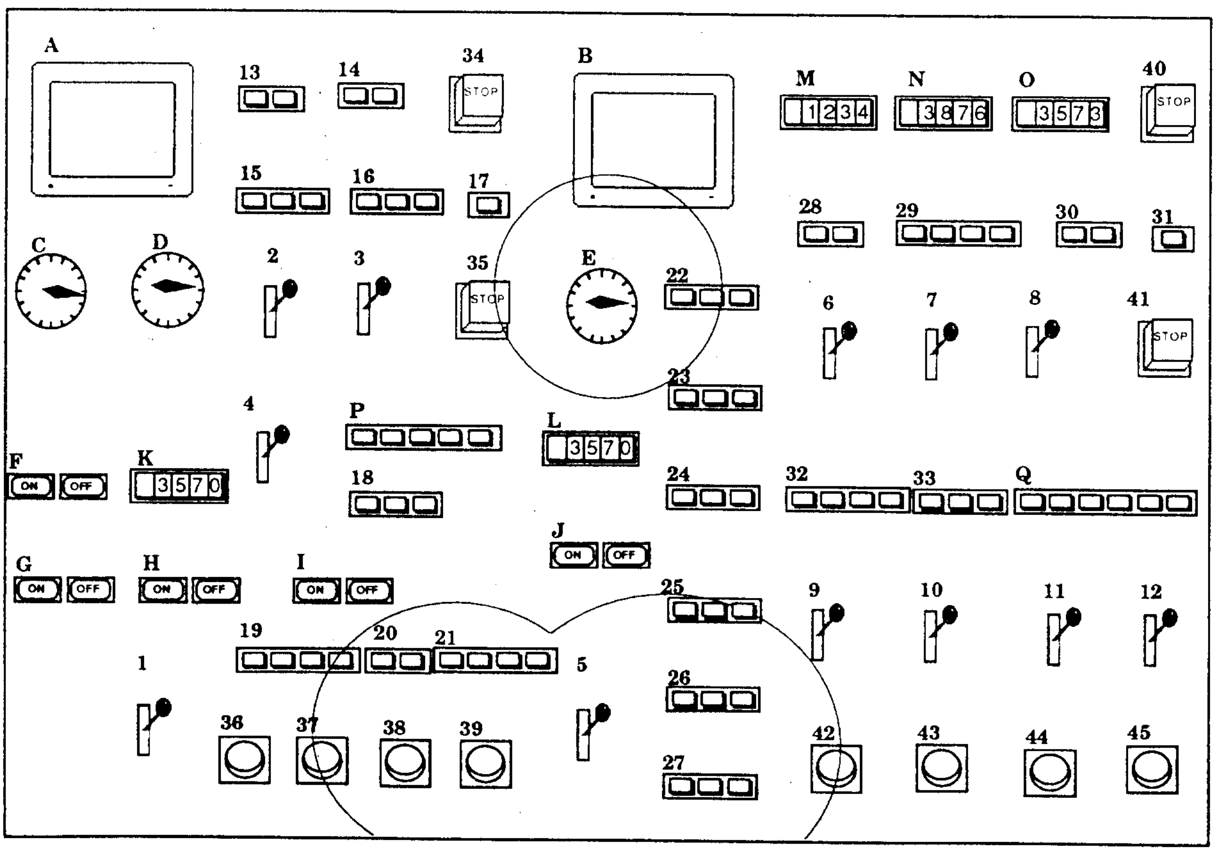

Figure 3. The current layout design for DEP02 panel

The critical instruments such as emergency stop buttons 34, 35, 40, and 41 were placed outside of reach area. It may yield a fatal accident in emergency. Some instruments which perform the same tasks were not placed adjacently, for example, the button lamp F indicating the status of a tandem cold mill (TCM) was located between the two displays C, G which show the position of a loop Car 3. In addition, The hand lever controls 6, 7, and 8 were arranged in the reverse sequence of the task flow. It causes the unnatural movement of the operator, and accordingly, can increase the discomfort. The displays M, N, and O also violate the principle of sequence-of-use. Between the controls 28 and 30 for the air jet adjustment, the control 29 performing the preparation of a tension leveler was located. It disturbs the smooth flow of task operation. The principle of spatial compatibility for the pairs of display and control (H-1, I-19, J-5, M-6, N-7, and O-8) are well reflected overall in the current layout.

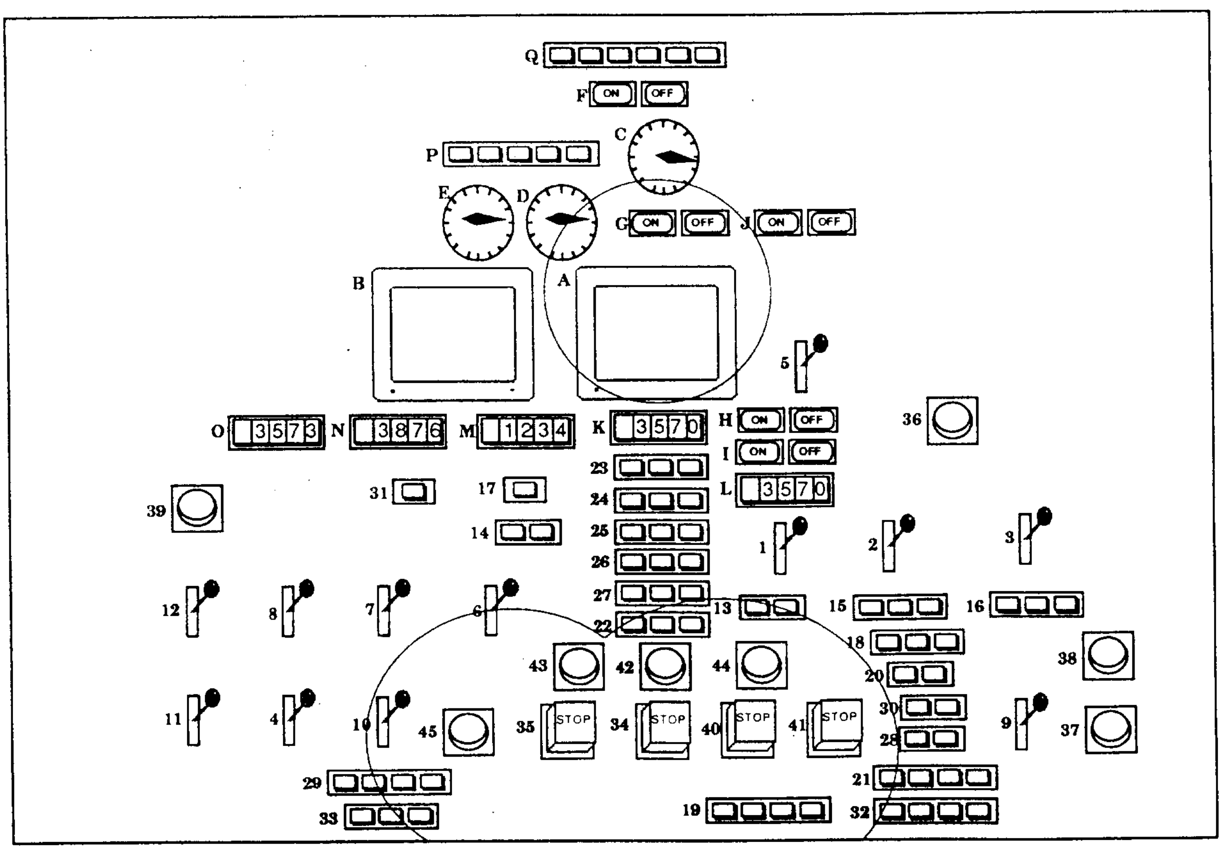

Figure 4 The new layout design for DEP02 panel

The prototype layout system creates a layout solution which follows the ergonomic design principles sufficiently. Figure 4 is redrawn from the computer-generated layout in Figure 2, in order to easily compare with the current layout. The displays A, D, and G were located in the preferred visual area according to the principle of frequency-of-use and importance. The controls 42, 43, 44, and 45 were located in the comfortable working area because these controls are frequently used in the control task. Especially, the operator can push the emergency stop buttons 34, 35, 40, and 41 easily and quickly since they were located within the reach boundary.

The controls (2, 3) and (13, 15, and 16) were properly arranged from left to right, and the controls (30, 28) and (8, 7, 6) , and the displays (O, N, M) were arranged in sequence in a way that the following instruments were located below the preceding instruments. And, all the instruments performing the same task such as (C, G), (2, 15), (3, 16), and (6, 7, 8, 10, 29, 33) were adjacently placed by the functional grouping principle. Also, the spatial compatibility principle for the pairs (H-1, I-19, J-5, M-6, N-7, and O-8) was well reflected in the layout solution. This layout evaluation indicates that the generated layout sufficiently reveals the design requirement from the task analysis.

The case study shows that the developed layout system can generate an ergonomically sound layout design. It is expected that the new layout design generated by the prototype layout system will improve work performance, and that the operator's overload can be avoid when the integration of the control room is accomplished.

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