Design and Implementation of a Fuzzy Elevator Group Control System

ChangBum Kim, Kyoung A. Seong, Hyung Lee-Kwang, *Member, IEEE*, and Jeong O. Kim

***Abstract*— Elevator group control systems (EGCS's) are the control systems that systematically manage three or more elevators in order to efficiently transport passengers. Most EGCS's have used the hall call assignment method to assign elevators in response to passengers' calls. This paper proposes a control strategy generation method, a hall call assignment method based on the fuzzy theory, and then the fuzzy elevator group control system (FEGCS). The control strategy of FEGCS is made using the classification of the passenger traffic and system manager's requirements, and the hall calls are assigned to suitable elevators by the generated control strategy. The system is operated using the given control strategy which is defined by the system manager. The proposed system shows better results than the conventional methods in simulations and is under commercialization by an industrial company.**

I. Introduction

ELEVATOR group control systems (EGCS's) are control systems that manage multiple elevators in a building in order to efficiently transport the passengers. The performance of EGCS's is measured by several criteria such as the average waiting time of passengers, the percentage of passengers waiting more than 60 s, and power consumption [14], [15], [18], [19]. EGCS's manage elevators to minimize the evaluation criteria; it is, however, difficult to satisfy all criteria at the same time. Therefore, the EGCS is designed to satisfy each criterion at certain levels. Nowadays, system managers want to define the control strategy of EGCS's, i.e., some managers want to reduce the average waiting time while others may want to reduce the power consumption.

An EGCS consists of *hall call* buttons, *car call* buttons, elevators, and a group controller. If a passenger wants to go to another floor, he presses a direction (hall call) button and waits for an elevator to arrive, then enters the elevator and presses a floor (car call) button in the elevator. The group controller selects a suitable elevator when a passenger presses the hall call button. In this case, the group controller considers the current situation of the building to select the most appropriate elevator in the group.

In the EGCS, it is difficult to select a suitable elevator for the following reasons. First, the EGCS is very complex. If a group controller manages n elevators and assigns p hall calls to the elevators, the controller considers n^p cases. Second, the controller must consider the hall calls which will be generated in the near feature. Third, it must consider many uncertain factors, such as the number of passengers at the floors where hall calls and car calls are generated. Fourth, it must be possible for a system manager to change the control strategy. Some managers want to operate the system to minimize passenger waiting time while others want to reduce the power consumption.

Many studies have been done and significant progress has been made regarding the algorithm to assign hall calls, but none of them are optimal solutions. Some recent studies [10], [12], [13], [15] show more desirable results than previous systems using conventional statistical methods. However, it is still difficult to define and reflect the control strategy and reflect the strategy when the EGCS selects suitable elevators.

The method in [10] used fuzzy logic to classify the traffic pattern, but the important features, such as the time and the ratio of in/out passengers, were not used as input variables. The method in [12] classified the traffic patterns and assigned the hall calls by using fuzzy logic, but it was difficult for the system manager to define control strategy. Control strategy defines control variables by vertical traffic type where the major concern is average waiting time in the morning, energy-consumption during business hours, and long-wait-percent in the evening. The method in [13] classified the traffic patterns and calculated waiting times by using a neural network. Hall calls were assigned by the waiting times, so it was difficult to consider the other evaluation criteria such as power consumption. Moreover, the system could not reflect the strategy. The method in [15] considered the control strategy generation, but used the conventional suitability functions at the hall call assignment, so it was difficult to reflect and tune the system for the control strategy.

Fuzzy theory has been used to make an approximate model when a system is very complex and it is not easy to make an accurate model for the system [1], [4], [5]. Many applications of fuzzy reasoning to construct advanced controllers have been reported [2], [3]. In this paper, we design and implement the fuzzy elevator group control system (FEGCS). Specifically, we focus on the *control strategy generation* and the *hall call assignment* parts of the FEGCS. The control strategy generation part prepares for the hall call assignment by using the system manager's request, and the hall call assignment part assigns hall calls to suitable elevators. The FEGCS shows more desirable results than other systems [11], [15].

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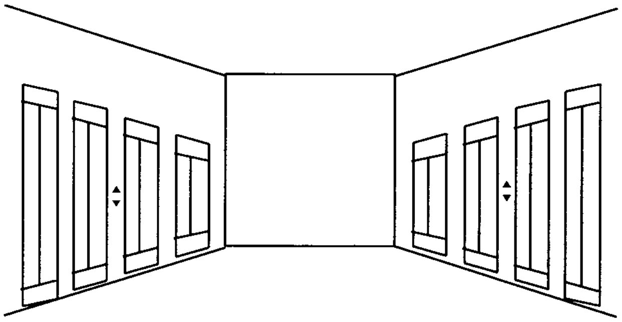

Fig. 1. A floor in a building where the EGCS is installed.

II. Elevator Group Control System

In this section, the general structure of EGCS will be discussed. There are two hall call (up, down) buttons on a floor, and multiple elevators as shown in Fig. 1. The EGCS selects an elevator for the passenger who has pressed a hall call button. The selected elevator moves to the floor where the hall call occurred. To understand the EGCS, consider an example of the elevator group control process.

1) A passenger who is going to the 15th floor from the second floor presses the up hall call button.
2) The hall call signal is transmitted to the EGCS.
3) The EGCS selects an elevator to service the passenger.
4) The EGCS sends a message to the selected elevator.
5) The selected elevator moves to the second floor and the passenger boards.
6) The passenger presses the car call button for the 15th floor.
7) The elevator sends a message to the EGCS and moves to the 15th floor.
8) The elevator arrives at the 15th floor and the passenger leaves.

The EGCS repeats the process of selecting service elevators for hall calls. We call the selection the *hall call assignment*. In the EGCS, the hall call assignment is important and the performance depends on the hall call assignment method.

Many evaluation criteria are used to estimate the performance of the EGCS [7], [8]. In this paper, the following three criteria are used.

1) *Average waiting time* (AWT) is the time until the service elevator arrives at the floor after a passenger presses a hall call button. AWT is the average of all waiting times in a unit time.
2) *Long waiting percent* (LWP) is the percentage of the passengers who wait more than 60 s in a unit time.
3) *RuN count* (RNC) is the number of elevator moves in a unit time and is used to estimate the power consumption of the system since most energy is consumed by starting or stopping the elevator.

Fig. 2 shows the general structure of the EGCS. In Fig. 2, the EGCS manages eight elevators in a building. Each elevator has its own controller represented by the car controller (CC) and communicates with the elevator group controller. The EGCS consists of three main parts and several modules.

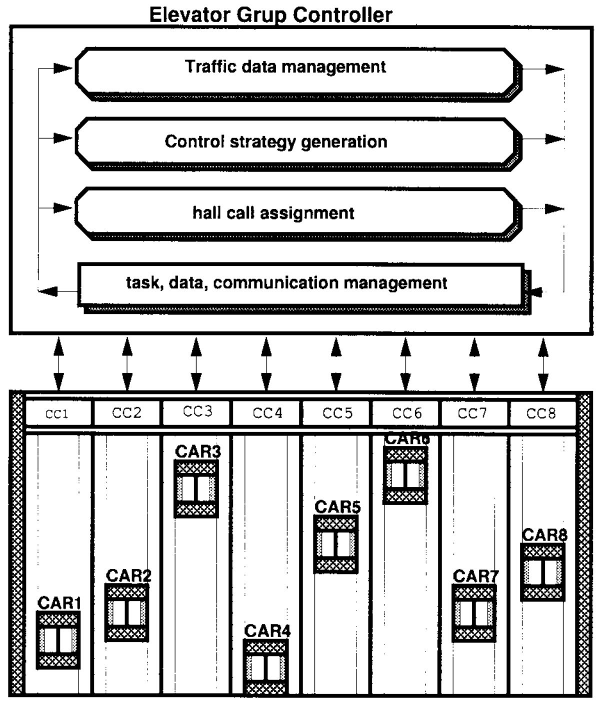

Fig. 2. General structure of the EGCS.

The three main parts are *traffic data management*, *control strategy generation*, and *hall call assignment*. The traffic data management part collects various statistics of traffic data such as the number of hall calls, car calls, and passengers getting on or off the elevators. This part learns the traffic data and predicts the future traffic [16], [17]. The control strategy generation part classifies the traffic into one of several modes and determines which hall call assignment method is suitable for the classified traffic mode. Finally, the hall call assignment part selects service elevators for hall calls via the method determined in the control strategy generation part. In addition, there are several small modules to support the main parts such as task management, data management, and communication management parts.

The EGCS generally tests the degree of suitability of each elevator for a hall call and selects an elevator with the best suitability. If we consider the above three evaluation criteria, then the suitability can be represented by their combination. Let ϕ_i be the suitability function for the ith elevator; $T_{AWT}(i), T_{LWP}(i)$, and $T_{RNC}(i)$ the evaluation values of ith elevator for AWT, LWP, and RNC, respectively; $T_{AWT}(i)$ the waiting time of the passenger; $T_{LWP}(i)$ the probability of the long waiting; and $T_{RNC}(i)$ the number of moves in a time interval when ith elevator assigns for the hall call. The suitability of ith elevator for a hall call can be represented by the following equation:

$$\phi(i) = v_1 \cdot T_{AWT}(i) + v_2 \cdot T_{LWP}(i) + v_3 \cdot T_{RNC}(i).$$

In this equation, the v_1, v_2, and v_3 are weighting factors of each evaluation criterion. The elevator with the minimum value of the function is selected.

III. Fuzzy Elevator Group Control System

The core parts of the FEGCS are the *control strategy generation* and the *hall call assignment*. In this section, the FEGCS will be introduced, and the presentation will focus on the core parts.

A. System Overview

Fig. 3 shows the structure of FEGCS. In Fig. 3, the FEGCS manages eight elevators and the status of the FEGCS is monitored via a terminal. The FEGCS consists of the traffic data generation, control strategy management, hall call assignment, data management, elevator management, and terminal management parts. The control strategy generation and the hall call assignment are the most important parts and have the most effect on the performance of FEGCS. They are new parts added to the conventional EGCS in this paper and the other parts are somewhat modified.

Traffic data management part manages traffic data of passengers by collecting, learning, and prediction. Traffic data, the number of passengers who get on/off elevators on each floor, is collected and learned periodically. Traffic data is predicted for the next unit time to help the hall call assignment.

Control strategy generation part classifies the passenger traffic data and makes a strategy for the hall call assignment. The passenger traffic data is classified into eight modes according to the characteristics of traffic using a fuzzy inference.

Hall call assignment part assigns the hall call to an suitable elevator considering the elevator status, passenger traffic, and control strategy.

Data management part manages all data of the FEGCS including elevator data, building data, statistic data, learning data, control strategy data, and membership function.

Elevator management part communicates with each elevator and collects data about the elevator status. The elevator status is given by specification, direction, position, door condition, hall call status, car call status, and weight.

Terminal management part communicates with a terminal and is necessary for the system manager. The system status including elevator status, control strategy, passenger traffic data, and system performance, is available at the terminal. Elevator specification, building specification, and system specification are changed through the terminal.

The key parts of interest here are the control strategy generation part and the hall call assignment part; these are discussed next.

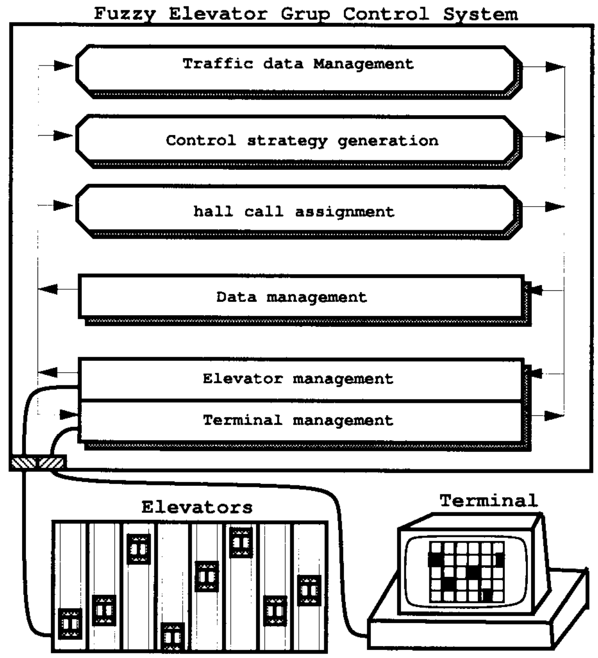

Fig. 3. Structure of the fuzzy elevator group control system.

B. Control Strategy Generation

The control strategy generation part prepares the hall call assignment part by making two types of control strategy. One is the *operation strategy* and the other is the *assignment strategy*.

The traffic pattern of passengers shows distinct characteristics according to the periods of time and it is easy to manage elevators by the traffic patterns [10]. Through our experience in operating the EGCS [15], we noted that it is more useful to divide the elevators into two groups at the up peak time, have stop some elevators unused at the inactive time, and to distribute the elevators at the business time. We call this the *operation strategy*.

In the hall call assignment part, hall calls are assigned by using fuzzy inference to satisfy the system manager's multiple objectives. The objectives are predefined by the system manager according to the traffic patterns. Several input variables and membership functions are used to assign the hall calls in the fuzzy inference. To reflect the objectives, we use different membership functions according to the traffic patterns. We call these sets of membership functions the *assignment strategy*.

The details of control strategy (operation strategy, assignment strategy) generation will be discussed next.

1) Operation Strategy Generation: In the operation strategy generation, the traffic data is classified into eight modes according to their characteristics. We will call the number of up-going passengers the *up traffic* and the number of down-going passengers the *down traffic*. Fig. 4 shows a typical up and down traffic pattern of an office building.

In Fig. 4, we can find clear differences between the traffic patterns around 9:00, 12:00, 13:00, and 18:00. So it is necessary to manage the elevators with different strategies according to the traffic patterns. For example, many passengers arrive at the lobby around 9:00. At that time, we must manage all elevators to go back to the lobby as soon as possible to minimize the AWT and LWP. However, we must consider the RNC to minimize the power consumption around 11:00, since the total traffic is medium at that time. In this section, we propose a traffic pattern recognition method based upon fuzzy logic.

We classify the passenger traffic patterns into eight traffic modes. Table I shows the traffic patterns.

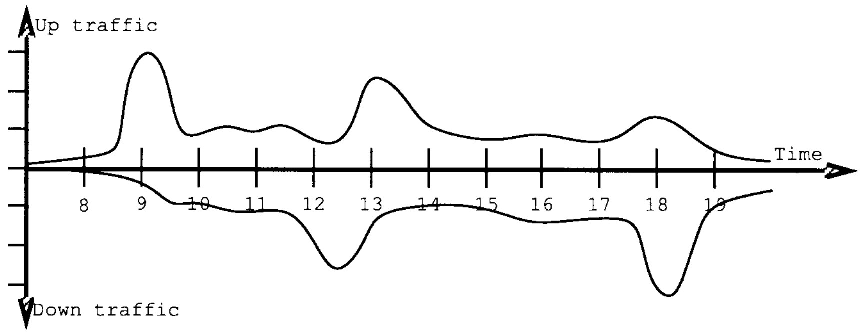

Fig. 4. Typical up and down traffic of an office building.

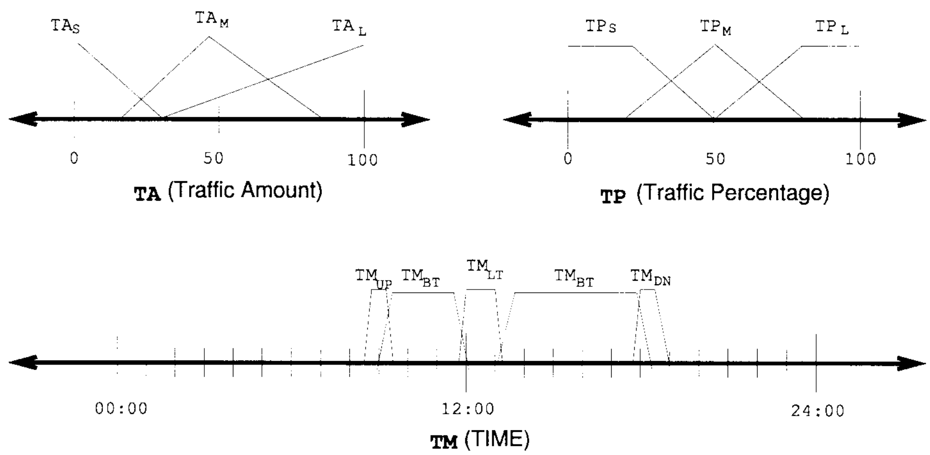

Fig. 5. Membership functions for the traffic feature.

TABLE I
PASSENGER TRAFFFIC PATTERNS

BT (Business Time)	Total traffic is medium Before and after noon
UP (Up Peak)	A lot of passengers come into a building Office-going hour
DP (Down Peak)	A lot of passengers go out from a building Closing hour
LT-A (Lunch Time A)	Most passengers go the restaurant Beginning of lunch time
IT (Inactive Time)	Total traffic is small Night
LT-B (Lunch Time B)	Most passengers go back to their office End of lunch time
BTH (Business Time and Heavy traffic)	Total traffic is large Anytime
HT (Heavy Traffic)	Many passengers gather into a floor and scatter from a floor Anytime

TABLE II
FEATURES OF PASSENGER TRAFFIC

UPT (UP Traffic)	Number of up going passengers
DNT (DownN Traffic)	Number of down going passengers
$CITP$ (Centralized In Traffic Percentage)	The ratio of the incoming passenger in the most crowded floor to that of all floors
$DOTP$ (Distributed Out Traffic Percentage)	The ratio of the outgoing passenger in all floors except the most crowde d floor to that of all floors
$TIME$	Current time

Incoming and outgoing passenger traffic data are collected at every floor for both directions. This amount of traffic information is too large to handle, but we can find features representing the traffic. The number of up/down going passengers is the most important piece of information, and the degrees of centralization and distribution of passengers on floors also give much information. The time is also important because some traffic occurs at similar times of day. Table II shows five important features representing the traffic characteristics.

The five features can be categorized into the traffic amount (TA), traffic percentage (TP), and time (TM). The UPT and DNT belong to TA, the $CITP$ and $DOTP$ to TP, and $TIME$ belongs to TM. Fig. 5 shows the linguistic terms and their membership functions used in the variables representing the traffic features. In Fig. 5, the TA_S, TA_M, and TA_L represent membership functions (small, medium, large) for

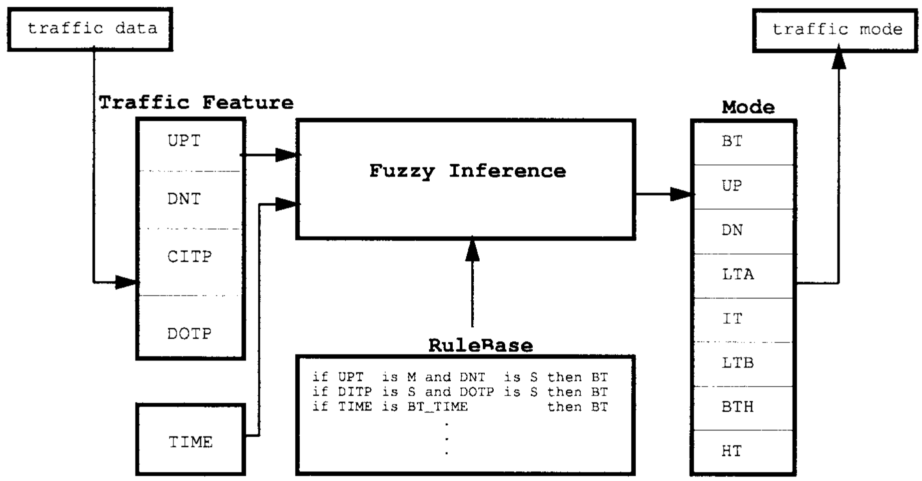

Fig. 6. Fuzzy classification of the passenger traffic.

the TA-type features and the TP_S, TP_M, and TP_L represent for TP type. The $TM_{UP}, TM_{BT}, TM_{LT}$, and TM_{DN} are membership functions for the TM.

The five features are used as input variables in the fuzzy inferencing model which gives the traffic mode as its output. Some fuzzy rules are given in the following, and the rules are grouped by the mode.

■ BT

- R_{11}) If UPT is TA_M and DNT is TA_M and $CITP$ is TP_S and $DOTP$ is TP_M and $TIME$ is TM_{BT} *then belongs to* BT
- R_{1j}) $\cdots\ \cdots$
- R_{1n_1}) If UPT is TA_M and DNT is TA_M and $CITP$ is TP_S and $DOTP$ is TP_L and $TIME$ is TM_{BT} *then belongs to* BT

■ UP

- R_{21}) If UPT is TA_L and DNT is TA_S and $CITP$ is TP_L and $DOTP$ is TP_M and $TIME$ is TM_{UP} *then belongs to* UP
- R_{2j}) $\cdots\ \cdots$
- R_{2n_2}) If UPT is TA_L and DNT is TA_S and $CITP$ is TP_L and $DOTP$ is TP_L and $TIME$ is TM_{UP} *then belongs to* UP.

Fig. 6 shows the structure of the fuzzy inference. Five features of current traffic are given for the fuzzy inferencing to classify the traffic pattern. Next, the fuzzy inference engine infers the possibility of each mode become the current traffic mode. After the inference, the traffic mode having the maximum possibility (α_{max}) is selected. If the possibility (α_{max}) of the selected traffic mode is more than α_{mode}, the control strategy is changed for this mode. If not, the previous control strategy is preserved. α_{mode} is a threshold which is a predefined constant and protects the oscillation of the traffic modes.

Let R_i be the rules for the ith traffic mode $(BT, UP, DP, LT-A, IT, LT-B, BTH, HT)$. The maximum possibility (α_{max}) is fuzzy inferred and max_mode is determined. Here m is the number of features, and n_i is the number of rules of R_i. α_i is the result of fuzzy inference for the ith traffic mode, and α_{ij} is the intermediate variable which represents the matching degree of jth rule in ith traffic mode. $\mu_{A_{ijk}}(x_k)$ is the matching degree of the ith mode, jth rule, and kth feature. $\mu_{A_{ijk}}(x_k)$ is an abstract presentation of membership functions in TA, TP, and TM. x_k is the kth feature $(UPT, DNT, CITP, DOTP, TIME)$.

$$\begin{aligned}\alpha_{ij} &= \prod_{k=1}^{m} \mu_{A_{ijk}}(x_k)\\ \alpha_i &= \max_{j=1}^{n_i} \alpha_{ij}\\ &= \max_{j=1}^{n_i} \left\{ \prod_{k=1}^{m} \mu_{A_{ijk}}(x_k) \right\}\\ \alpha_{max} &= \max(\alpha_1, \alpha_2, \cdots, \alpha_{n_i})\\ max\_mode &= k, (\alpha_k = \alpha_{max}).\end{aligned}$$

The max_mode is determined by the comparison with the maximum possibility (α_{max}). Let *mode* be the traffic mode determining the control strategy. The *mode* is set by the following equation. The threshold α_{mode} is used to protect the oscillation of traffic mode when the traffic mode is changed from one to another

$$mode = max\_mode, \quad if\ \alpha_{max} > \alpha_{mode}.$$

2) Assignment Strategy Generation: In the hall call assignment part, each elevator is tested on the evaluation criteria (AWT, LWP, RNC) to get the suitabilities of the elevators

TABLE III
INPUT VARIABLES

$HCWT_i$ (Hall call Waiting Time)	Waiting time until arrival the i-th elevator at the floor for a hall call from the current position
$maxHCWT_i$ (maximum Hall call Waiting Time)	Maximum of $HCWT_i$ for assigned hall calls to the i-th elevator
CV_i (Coverability)	The capability of the elevator group control system for future hall calls to the i-th elevator.
GD_i (Gathering Degree)	Minimum distance from a new hall call to the hall and car calls assigned i-th elevator

by using a fuzzy inference, and an elevator is selected to assign the hall call. At that time, the elevator having the largest overall suitability is selected.

Let w_1, w_2, and w_3 be real values in [0,1] which represent the degree of importance for the evaluation criteria (AWT, LWP, RNC), respectively. The system manager's objectives can be represented as (w_1, w_2, w_3) to each traffic mode. If a system manager defines the importance degrees as (1.0, 0.8, 0.4) in the business time, it means that he wants to minimize the average waiting time of the passengers and considers energy use not as important. Generally, the AWT and LWP are more important at the heavy traffic modes (UP, DP, LT-A, LT-B, BTH, HT) and the RNC is important at the light traffic modes (BT, IT).

To reflect the importance degrees (w_1, w_2, w_3), the suitabilities are inferred to different values by the importance degrees for the same condition. For example, the suitability of an elevator (average waiting time is reduced if we assign the elevator) is inferred to be a larger value when the importance degree of the AWT is defined larger. Therefore, the hall call assignment is highly affected by the control variables related to an evaluation criterion, if we define high importance degree for the evaluation criterion.

In the hall call assignment part, the suitability of each evaluation criterion is fuzzy inferred using the input variables $HCWT_i, maxHCWT_i, CV_i$, and GD_i, and membership functions, respectively. Brief definitions of input variables are shown in Table III, and details of the estimation methods will be presented in the hall call assignment part. The input variables are very closely related to the evaluation criteria and can be estimated. The membership functions are only changed to reflect the importance degrees. The assignment strategy generation part generates the membership functions by the importance degrees and the classified traffic mode.

The $HCWT_i$ is related to the AWT, the $maxHCWT_i$ to the LWP and RNC, the CV to the AWT and LWP, and GD_i to the RNC. Two membership functions (Small, Large) for each input variable are used and shown in Fig. 7.

In the assignment strategy generation part, the membership functions that will be used in hall call assignment are made by the importance degrees of the classified traffic mode. The importance degree is defined in evaluation criteria

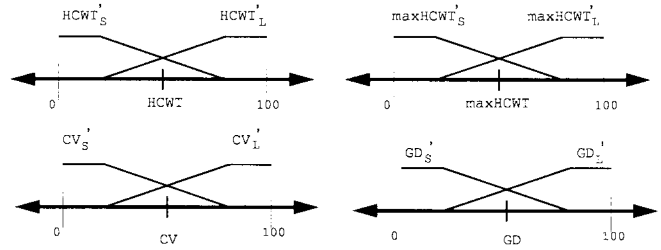

Fig. 7. Membership functions of input variables.

(AWT, LWP, RNC) but the inference of the hall call assignment used different variables. The relations between evaluation criteria and input variables are applied to get the importance degree of input variables.

For example, if the importance of AWT is defined as a larger value, EGCS should assign hall calls to minimize the AWT. The major factors of the input variables are $HCWT$ and CV by the relation of input variable and evaluation criteria. Therefore, the suitability of an elevator for the evaluation factor AWT is inferred by using the input variables $HCWT$ and CV in the hall call assignment. The rule of the inference needed the matching degrees ($HCWT_S(\ ) = 1, HCWT_L(\ ) = 0, CV_S(\ ) = 0, CV_L(\ ) = 1$) to get the largest suitability for the AWT. If we make the membership functions generate more desirable values for the same input, the suitability of an elevator for the evaluation factor AWT becomes larger and means that the importance degree of AWT is applied in the process of hall call assignment.

The membership functions are generated by shifting from the basic membership functions as shown in Fig. 7. The shifting of membership functions is defined by the importance degree and the desirable matching degree of each input variable. The importance degree of input variables is made by the minimum operation of the importance degree of related evaluation criteria. The shifting rule is shown in Table IV.

If the importance of HCWT is defined to be a large value, then we shift the basic membership function $HCWT'_S$ (small) to the right and $HCWT'_L$ is shifted left. Through the shift, the matching degree of the $HCWT_S$ becomes larger and means that the HCWT becomes a more important factor in the hall call assignment.

Let W $(W_{HCWT}, W_{maxHCWT}, W_{CV}, W_{GD})$ be the maximum shifts of the input variables. The values of maximum shifts are given by system developer and means the limit of the shifting from basic membership function in Fig. 7. The w_1, w_2, and w_3 are the importance degrees of evaluation criteria defined by operator. The membership functions will be used in the hall call assignment as follows:

$$HCWT_S(x) = HCWT'_S(x - ((w_1 - 0.5) \cdot W_{HCWT}))$$
$$HCWT_L(x) = HCWT'_L(x - ((w_1 - 0.5) \cdot W_{HCWT}))$$
$$maxHCWT_S(x)$$

TABLE IV
SHIFTING RULE OF MEMBERSHIP FUNCTIONS

variable name	related criteria	membership function	desirable matching degree	shifting direction	
				importance < 0.5	importance > 0.5
$HCWT$	AWT	$HCWT_S$	1.0	left	right
		$HCWT_L$	0.0	left	right
$maxHCWT$	LWP, RNC	$maxHCWT_S$	1.0	left	right
		$maxHCWT_L$	0.0	left	right
CV	AWT, LWP	CV_S	0.0	right	left
		CV_L	1.0	right	left
GD	GD_i, RNC	GD_S	0.0	right	left
		GD_L	1.0	right	left

$$= maxHCWT'_S(x - (((w_2 \wedge w_3) - 0.5) \cdot W_{maxHCWT}))$$

$$maxHCWT_S(x) = maxHCWT'_S(x - (((w_2 \wedge w_3) - 0.5) \cdot W_{maxHCWT}))$$

$$CV_S(x) = CV'_S(x - (((w_1 \wedge w_2) - 0.5) \cdot W_{CV}))$$

$$CV_L(x) = CV'_L(x - (((w_1 \wedge w_2) - 0.5) \cdot W_{CV}))$$

$$GD_S(x) = GD'_S(x - ((w_3 - 0.5) \cdot W_{GD}))$$

$$GD_L(x) = GD'_L(x - ((w_3 - 0.5) \cdot W_{GD})).$$

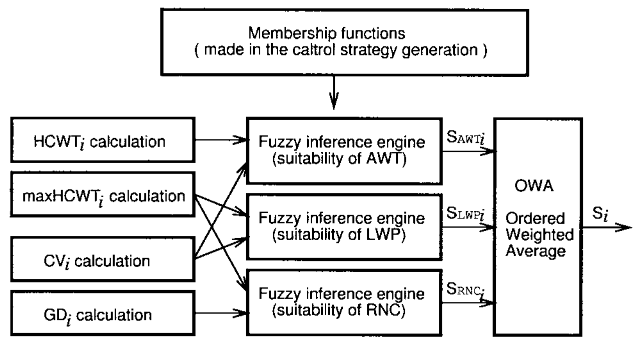

Fig. 8. Inference structure of the overall suitability.

We call the preparation of membership functions assignment strategy generation. In this process, the importance degrees of evaluation criteria are applied to the hall call assignment.

C. Hall Call Assignment

The hall call assignment part assigns hall calls to the suitable elevators whenever new hall calls occur. Three fuzzy inferences are implemented to test the suitability of each evaluation criterion, and an ordered weighted average (OWA) [20] operation is employed to get the overall suitability of each elevator. Finally, the elevator having the largest overall suitability is selected to service the new hall call.

Fig. 8 shows the inference structure of the overall suitability of the ith elevator. In Fig. 8, the suitability of each evaluation criterion $(S_{AWT_i}, S_{LWP_i}, S_{RNC_i})$, is inferred, and then overall suitability (S_i) is calculated.

1) Calculation of Input Variables: The hall call assignment part considers data such as the direction and floor of hall calls, condition of elevators, and future hall calls. These data reflect the suitability of each elevator according to the evaluation criteria. Since the evaluation criteria can be computed after the hall calls are assigned, the AWT, LWP, and RNC are estimated using the $HCWT, maxHCWT, CV$, and GD.

The input variables of the fuzzy inference are hall call waiting time ($HCWT$), maximum hall call waiting time ($maxHCWT$), coverability (CV), and gathering degree (GD). Each input variable is calculated for each elevator when a hall call occurs. In the calculation, we assume the hall call is assigned to the ith elevator. Let f be the number of floors and n be the number of elevators. The followings are the calculation methods:

- $HCWT_i$
  Waiting time until arrival the ith elevator
  at the floor for a hall call from the current position.
  - $HCWT_i$ = moving_time + stop_time
    - ◇ moving_time = normal_speed_floors · normal_time_per_floor + speed_up_floors · speed_up_time + speed_down_floors · speed_down_time
    - ◇ stop_time = $\sum$(door_opening_time + in_out_time + door_closing_time)
- $maxHCWT_i$
  Maximum waiting time of hall calls for the ith elevator.
  - maxHCWT$_i$ = max (assigned_hall_call_waiting_times, new_hall_call_waiting_time)
    - ◇ assigned_hall_call_waiting_times = HCWT for the assigned hall calls
    - ◇ new_hall_call_waiting_time = $HCWT_i$

- CV_i
  The capability of the elevator group control system for future hall calls to the ith elevator.
  - $CV_i = 1 - \frac{err\_traffic}{in\_traffic}$
    - ◇ in_traffic = number of passengers who try to get on elevator in an unit time $= \sum_{j=1}^{f}$ incoming passengers at jth floor
    - ◇ err_traffic = number of passengers that cannot be serviced in an unit time $= \sum_{j=1}^{f}\sum_{k=1}^{n}$ (in_traffic$_j -$ capacity$_{jk}$)
      $capacity_{jk}$ = the number of persons could get on kth elevator on jth floor
- GD_i:
  Minimum distance between the position of the new hall call and hall calls and car calls assigned ith elevator.
  - $GD_i = \frac{1}{min\_distance}$
    - ◇ min_distance $= min_{j=1,\cdots,number\_of\_assigned\_calls}$ Distance(new_hall_call, assigned_call).

2) Fuzzy Inference: Three fuzzy rule sets are derived to infer the suitability of each evaluation criterion. The suitability of AWT_i is inferred using the input values $HCWT_i$ and CV_i, the LWP_i is $maxHCWT_i$ and CV_i, and the RNC is $maxHCWT_i$ and GD_i.

The fuzzy rule sets inferencing the suitabilities are as follows:

- Suitability of the AWT_i
  - If $HCWT_i$ is $HCWT_S$ and CV_i is CV_L then S_{AWT_i} is LARGE
  - If $HCWT_i$ is $HCWT_S$ and CV_i is CV_S then S_{AWT_i} is MEDIUM
  - If $HCWT_i$ is $HCWT_L$ and CV_i is CV_L then S_{AWT_i} is MEDIUM
  - If $HCWT_i$ is $HCWT_L$ and CV_i is CV_S then S_{AWT_i} is SMALL
- Suitability of the LWP_i
  - If $maxHCWT_i$ is $maxHCWT_S$ and CV_i is CV_L then S_{LWP_i} is LARGE
  - If $maxHCWT_i$ is $maxHCWT_S$ and CV_i is CV_S then S_{LWP_i} is MEDIUM
  - If $maxHCWT_i$ is $maxHCWT_L$ and CV_i is CV_L then S_{LWP_i} is MEDIUM
  - If $maxHCWT_i$ is $maxHCWT_L$ and CV_i is CV_S then S_{LWP_i} is SMALL
- Suitability of the RNC_i
  - If $maxHCWT_i$ is $maxHCWT_S$ and GD_i is GD_L then S_{RNC_i} is LARGE
  - If $maxHCWT_i$ is $maxHCWT_S$ and GD_i is GD_S then S_{RNC_i} is MEDIUM
  - If $maxHCWT_i$ is $maxHCWT_L$ and GD_i is GD_L then S_{RNC_i} is MEDIUM
  - If $maxHCWT_i$ is $maxHCWT_L$ and GD_i is GD_S then S_{RNC_i} is SMALL.

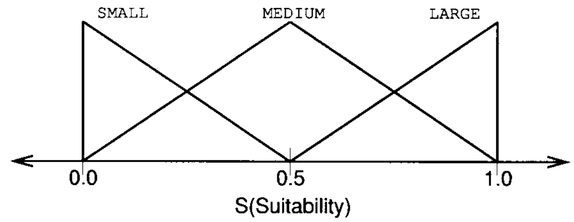

Fig. 9. Linguistic terms defined in the suitability domain.

In the rule sets, $SMALL, MEDIUM$, and $LARGE$ are linguistic terms defined in the suitability domain, and commonly used in three inferences. Fig. 9 shows the linguistic terms $SMALL, MEDIUM$, and $LARGE$. In the fuzzy inferences, Mamdani's method and center of gravity method are used for inferencing and defuzzification, respectively.

The OWA [20] operator is used to aggregate the suitabilities of evaluation criteria. The OWA operator is an aggregation operator which forms an overall decision function in a multicriteria problem and is defined as follows.

Definition: A mapping F from

$$I^n \rightarrow I \text{ (where } I = [0, 1])$$

is called an OWA operator of dimension n if associated with F and is a weighting vector W

$$W = \begin{bmatrix} W_1 \\ W_2 \\ \cdot \\ W_n \end{bmatrix}$$

such that $W_i \in (0, 1), \Sigma\, W_i = 1$ and where

$$F(a_1, a_2, \cdots, a_n) = W_1 b_1 + W_2 b_2 + \cdots + W_n b_n$$

where b_i is the ith largest element in the collection $a_1, a_2, \cdots, a_n$.

In this paper, $W^T = [0.50.3, 0.2]$ is used to emphasize the criteria having the largest suitability. The S_{AWT_i}, S_{LWP_i}, and S_{RNC_i} are the suitability of each evaluation criterion, and the S_i is the overall suitability of ith elevator. Therefore, the S_i is aggregated by the following:

$$S_i = F(S_{AWT_i}, S_{LWP_i}, S_{RNC_i}).$$

By the above methods, the overall suitability of elevators $S_1, S_2, \cdots, S_n$ are inferred where the n is the number of elevators in the elevator group control system.

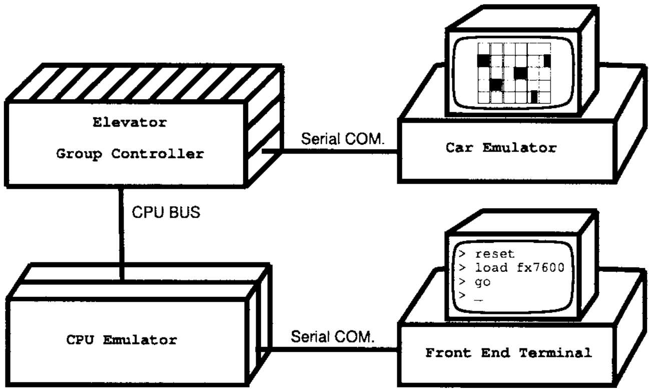

Fig. 10. Simulation environment.

Finally, the hall call assignment part selects an elevator having the largest overall suitability. Let e be a selected elevator to service the new hall call. The e is defined as

$$e \in 1, 2, \cdots, n \text{ such that } S_e = \max(S_1, S_2, \cdots, S_n).$$

In this selection mechanism, the importance degrees defined by the system manager are affected in the following way. First, the membership functions defined by the input variables are made by the importance degrees. Second, the suitability of each evaluation criterion is inferred using the membership functions. At that time, the suitability will be increased when the system manager defines the importance degree to large value. Third, the OWA operation aggregates three suitabilities. Finally, an elevator having the largest overall suitability is selected. Therefore the importance degrees are applied to the hall call assignment.

IV. Experimental Results and Analysis

We have implemented a simulation environment to evaluate the proposed elevator group control system's performance. The simulation environment consists of four parts as shown in Fig. 10. The first part is a real elevator group controller and the second part is a central processing unit (CPU) emulator which is used for convenience of programming and debugging. The third part is a car emulator which generates hall calls and car calls like real elevators. It collects and displays the statistics of the simulation. The car emulator is developed on an IBM PC. The final part is a front end terminal. We use another PC to program and debug our elevator group control system. In the simulation environment, we used real hardware from an elevator group control system and developed a car emulator which simulates the elevator's movement and operations.

We have performed numerous experiments to test the performance of the system and will show some experimental results in the following. In the simulation, the AWT is measured in tenths of seconds (0.1 s) and the LWP is in tenths of a percent (0.1%). The RNC is interpreted as the power consumption.

A. Overall Performance Evaluation

We simulated and compared the FEGCS with other systems in our simulation environment. The compared systems are the conventional system as in [11] and our previous work [15]. For the simulation, real traffic data of the SS Building in Seoul, Korea, was used.

TABLE V
THE CONDITIONS OF SIMULATION

number of floors	18
number of elevators	6
elevator speed	180 m/min
elevator capacity	24 man
simulation time	12:00 ~ 15:00
simulation data	SS building, April, 1992
number of passengers	12:00 ~ 12:30 : 300 man/5min
	12:30 ~ 13:30 : 200 man/5min
	13:30 ~ 15:30 : 100 man/5min

TABLE VI
THE SIMULATION RESULTS

		Hitachi81	Bum95	new	improv. Hitachi81(%)	improv. Bum95(%)
before lunch 12:00~12:40	AWT	238	202	179	25	11
	LWP	83	51	42	50	17
after lunch 12:40~13:20	AWT	248	246	211	15	10
	LWP	94	86	75	21	12
business time 13:20~15:00	AWT	240	218	207	14	5
	LWP	69	68	40	43	41
total 12:00~15:00	AWT	242	221	197	19	10
	LWP	82	68	59	35	13

The FEGCS and conventional systems were simulated to evaluate the total performance from 12:00 to 15:00. For that time frame, the membership functions and importance degrees are tuned appropriately. The conditions of simulation are shown in Table V. According to the traffic pattern, the simulation situation is divided into several periods such as before lunch time (12:00 ~ 12:40), after lunch time (12:40 ~ 13:20), and business time (13:20 ~ 15:00).

The performance is measured by using the criteria of AWT and average LWP because they are two important criteria in the elevator system. The simulation results are shown in Table VI where "Hitachi81" indicates the conventional system [11], "Bum95" the previous system [15], "new" the FEGCS, and "improv.1" the improvement compared with "Hitachi81" and "improv.2" with "Bum95".

As shown in Table V, AWT and LWP are improved in all time periods. AWT is improved by 19% and LWP by 35% compared with "Hitachi81," and AWT by 10% and LWP by 13% compared with "Bum95" in the total periods. In the simulation results, the overall performance of FEGCS is increased in all time periods. Therefore, we decided that this developed system is worth commercializing.

B. Effect of the Importance Degrees

The effect of change in the importance degree of each evaluation criterion (AWT, LWP, RNC) is tested by the

TABLE VII
THE CONDITIONS OF SIMULATION

number of floors	18
number of elevators	6
elevator speed	180 m/min
elevator capacity	24 man
simulation time	14:00 ~ 15:00
simulation data	twin building, April, 1992
number of passengers	100 man/5min

TABLE VIII
SIMULATION RESULTS USING THE DIFFERENT IMPORTANCE DEGREES

Importances	Simulation results		
(AWT, LWP, RNC)	AWT	LWP	RNC
(0.5, 0.5, 0.5)	241	38	145
(0.7, 0.5, 0.5)	227	39	146
(0.9, 0.5, 0.5)	206	41	141
(0.5, 0.7, 0.5)	239	29	141
(0.5, 0.9, 0.5)	244	22	143
(0.5, 0.5, 0.7)	244	40	129
(0.5, 0.5, 0.9)	260	48	121

following simulation. 0.5 was used for the initial values of importance degrees. The FEGCS was also simulated using importance degrees (0.7, 0.5, 0.5), (0.9, 0.5, 0.5), (0.5, 0.7, 0.5), (0.5, 0.9, 0.5), (0.5, 0.5, 0.7), and (0.5, 0.5, 0.9). The conditions of simulation are shown in Table VII, and the simulation results of the FEGCS are given in Table VIII.

In the simulation result, we see that AWT is decreased to 227 and 206 when we use the importance degree of AWT (0.7 and 0.9). LWP is decreased (29 and 22) for high importance degree (0.7 and 0.9), and RNC to (129 and 121) for (0.7 and 0.9), respectively. It shows that the performance of an evaluation criterion defined as having a high importance degree is increased. This is a very desirable result because the performance of FEGCS can be changed by the importance degrees. Therefore, system managers can define their aims on the evaluation criteria and the FEGCS reflects the importance degrees.

V. CONCLUSIONS

In this study, the FEGCS is designed and implemented to increase the performance of elevator systems. The control strategy generation and hall call assignment parts, which are the most important parts of the FEGCS, are developed and the FEGCS is tested by computer simulation.

In the control strategy generation part, the passenger traffic patterns are classified, and the membership functions used at the hall call assignment are made by the classified traffic mode and importance degrees of the evaluation criteria. In the hall call assignment part, the hall calls are assigned to the suitable elevators to service passengers. The suitabilities of elevators for a hall call is given by the fuzzy inference and the system selects an elevator by the rank of the overall suitability.

The change effect of importance degrees on the evaluation criteria was tested by the simulation and shows desirable results. According to the simulation, the performance of an evaluation criteria is increased when we use a high-importance degree for that criteria. The result means that the FEGCS can operate according to the given control strategy. The overall performance of the FEGCS was tested for several traffic conditions. By the simulation result, it is noted that the overall performance of the FEGCS is increased in all time periods. The FEGCS is now being commercialized by the Star Industrial Systems Corporation.

REFERENCES

[1] L. A. Zadeh, "Outline of new approach to the analysis complex systems and decision processes," *IEEE Trans. Syst., Man, Cybern.*, vol. SMC-3, pp. 28–44, 1973.
[2] E. H. Mamdani, "Application of fuzzy algorithms for control of simple dynamic plant," in *IEEE Proc. Control Science*, 1974, vol. 121, no. 12, pp. 1285–1588.
[3] M. Sugeno and K. Murakami, "An experimental study on fuzzy parking control using a model car," *Ind. Applicat. Fuzzy Contr.*, pp. 125–138, 1985.
[4] C. C. Lee, "Fuzzy logic in control systems: Fuzzy logic controller—part I," *IEEE Trans. Syst., Man, Cybern.*, vol. 20, pp. 404–418, 1990.
[5] ——, "Fuzzy logic in control systems: Fuzzy logic controller—part II," *IEEE Trans. Syst., Man, Cybern.*, vol. 20, pp. 419–435, 1990.
[6] H. J. Zimmermann, *Fuzzy Set Theory and Its Applications*. Norwell, MA: Kluwer, 1991.
[7] Y. S. Song, "A comparative study of fuzzy implication operators: An application to elevator systems," M.S. thesis, Dept. Comput. Sci., Korea Adv. Inst. Sci. Technol., Taejon, Korea, 1992.
[8] J. B. Lee, "A study on the development of optimal model for determining configurations of the elevator systems," M.S. thesis, Hanyang Univ., 1988.
[9] G. R. Strakosch, *Vertical Transportation: Elevators and Escalators*. New York: Wiley, 1983.
[10] M. L. Siikonen and J. Leppala, "Elevator traffic pattern recognition," in *Proc. 4th IFSA Congr.*, 1991, pp. 195–198.
[11] Hitachi, Ltd., "Group supervisory system of elevator cars," U.S. Patent 4 244 450, 1981.
[12] ——, "The fuzzy elevator group supervisory system," Japan Patent 2-52875, 1992.
[13] Mitsubishi, Ltd., "Group supervisory system of elevator cars based on neural network," Japan Patent 4-32472, 1992.
[14] C. B. Kim, K. A. Seong, and H. Lee-Kwang, "Fuzzy approach to elevator group control system," in *Proc. 5th IFSA Congr.*, 1993, vol. 2, pp. 1218–1221.
[15] ——, "A fuzzy approach to elevator group control system," *IEEE Trans. Syst., Man, Cybern.*, vol. 25, pp. 985–990, June 1995.
[16] R. Lutfi and G. C. Barney, "The inverse S-P method deriving lift traffic patterns from monitored data," Control Systems Centre rep. 745, 1991.
[17] ——, "The use of moving average in filtering lift traffic patterns," Control Systems Centre rep. 747, 1991.
[18] R. D. Peters, "The theory and practice of general analysis lift calculations," in *Elevcon Proc.*, 1992, pp. 197–206.
[19] G. C. Barney and S. M. dos Santos, *Elevator Traffic Analysis, Design, and Control*. Stevenage, U.K.: Peregrinus, 1985.
[20] R. R. Yager, "On ordered weighted averaging aggregation operators in multicriteria decision making," *IEEE Trans. Syst., Man, Cybern.*, vol. 18, pp. 183–190, Jan./Feb. 1988.

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