Indoor Platoon Driving of Electric Wheelchair with Model Error Compensator along Wheel Track of Preceding Vehicle

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***Abstract*—As one of the leading method of electric wheelchairs, platoon driving using Adaptive Cruise Control (ACC) has been proposed to keep constant time-headway. The platoon driving system has been widely used assuming straight roads that has good visibility, but has not been used in narrow corridor. While, the gross weight of wheelchair changes drastically depending on passenger's weight. In this paper, a novel platoon driving system is proposed for narrow corridor driving. The platoon controller is constructed with the inter-vehicle distance control based on ACC and precise lateral control based on target point following along wheel track of preceding wheelchair. The effectiveness of the proposed method is verified by the driving experiments at the corner in narrow corridor.**

I. INTRODUCTION

In aging societies, the electric wheelchairs have been widely used. An electric wheelchair STAVi has been developed for elderly and handicapped persons [1]. STAVi has a unique piggybacking design that allows the user to climb into the wheelchair in a comfortable manner.

In hospitals and care facilities, the care worker have to take care of many patients who use wheelchair at the same time. As one of the leading method of many wheelchairs, the platoon driving using Adaptive Cruise Control (ACC) has been proposed [2] [3]. The platoon driving is assumed to be used at a straight road that has good visibility. Because of narrow corridor without good visibility, it is difficult to guide many wheelchairs in single file by common ACC technology.

There are two important issues in indoor platoon driving of electric wheelchairs. First, the dynamic characteristic of a wheelchair is affected by the passenger's weight or other driving conditions, because a wheelchair is lighter than a car. As the modeling error makes the platoon unstable, the robust controller which suppresses modeling error is required. Second, in order to avoid collision against a wall, the following vehicle must precisely track along the trajectory of preceding vehicle. Therefore, we must design a precise following controller in stable platoon driving.

In this paper, a novel platoon driving system is proposed in narrow corridor based on ACC with Modeling Error Compensator (MEC) [4]. The platoon controller is constructed for each wheelchair considering precise and stable driving. At first, the inter-vehicle distance control based on ACC is designed, and the modeling error depending on passenger's weight is suppressed by MEC. Next, the lateral control based on target point following algorithm using way point is designed [5], and the precise following along wheel track of the preceding vehicle is achieved. Finally, the effectiveness of proposed method is evaluated by a platoon driving experimented at a corner of narrow corridor in the building.

II. ISSUES OF PLATOON DRIVING IN NARROW SPACE

Piggyback type personal wheelchair STAVi was developed for elderly and handicapped persons [1]. STAVi has a unique piggybacking design that allows the user to climb into the wheelchair in a comfortable manner. The seat height can be adjusted based on user preferences and then be raised back to the driving position to maintain the user's eye line as their standing position.

Here, we consider the driving scene of STAVi in the hospital or the care facility. The care worker often leads patients to rehabilitation or exercise area by electric wheelchairs. The care worker must pay attention to all patients whose recovery level or driving ability are different. If the care worker leads some patients by platoon, patients' and care person's burden will be reduced. However, there are few platoon control systems of wheelchair to drive in narrow space, and the control method suitable for practical use has been studied.

Fig.1 shows a demonstration with STAVi at outdoor. Here, simple ACC algorithm was applied. In this demonstration, the 1st carriage (STAVi♯2) is driven by a conductor. 2nd one (STAVi♯3) is electric wheelchair, and 3rd one is a carrier. A conductor sometimes leads wheelchairs without passengers. The difficulty of platoon driving is attributable to time constant and/or center of gravity changes according to passenger's or baggage weight. Also, it is difficult for simple ACC to realize a precise driving for narrow corridor.

Fig. 1. Driving demonstration with electrical wheelchair STAVi

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The objective of our research is to design indoor platoon driving controller which suppresses parameter variations by passenger's weight and follows the preceding wheelchair in narrow corridor precisely.

III. PLATOON DRIVING USING ACC

A. Adaptive Cruise Control

There are two methods for platoon driving; one is the Constant Inter-vehicle Distance (CID) control, the other is the Constant Time-Headway (CTH) control. The CID control keeps constant inter-vehicle distance even though the preceding wheelchair changes its velocity. On the other hand, the CTH control keeps the time-headway. Therefore, inter-vehicle distance changes according to driving velocity. If the leading wheelchair drives fast, inter-vehicle distance becomes large. In contrast, the CID control has an advantage that inter-vehicle distance becomes shorter. However, it is difficult to satisfy string stability conditions in case that desired inter-vehicle distance is short. By using the CTH control, it becomes easy to satisfy string stability condition with simple velocity feedback using own vehicle information. Therefore, we apply the CTH control called ACC to the platoon driving system.

Here, the ACC systems will be outlined. The relationship between the preceding and the following wheelchair is shown in Fig.2. v_i is a wheelchair velocity and d_i is an inter-vehicle distance. Suffix i and $i-1$ are the following and the preceding wheelchair number, and $i = 1$ indicates the leading wheelchair.

The dynamics from control input u_i to wheelchair velocity v_i is assumed as follows;

$$G_i(s) = \frac{v_i}{u_i} = \frac{1}{\tau_i s + 1} \ , \tag{1}$$

where τ_i represents the time constant.

The desired inter-vehicle distance d_{ri} is represented by the multiplication of wheelchair velocity v_i and desired time-headway T. The time-headway is arrival time of the following to the preceding wheelchair. The desired inter-vehicle distance is defined as follows;

$$d_{ri} = Tv_i + d_0 \ , \tag{2}$$

where d_0 is standstill distance. ε_i, z_i and $\dot{d}_i$ represent distance error $\varepsilon_i = d_i - d_{ri}$, integral of distance error and derivative of distance error $\dot{d}_i = v_{i-1} - v_i$. The control input for $G_i(s)$ is designed as follows;

$$u_i = K_1 \dot{d}_i + K_2 \varepsilon_i + K_3 z_i \ , \tag{3}$$

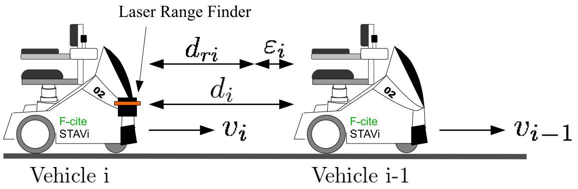


Fig. 2. Relation between the preceding and the following wheelchair

where $K_j (j = 1, 2, 3)$ are feedback gain of ACC calculated by the optimal servo [6].

Fig.3 shows block diagram of ACC. $G_i(s)$ represents the transfer function of wheelchair in eq.(1). H represents the spacing policy shown in eq.(2). And $K(s)$ represents ACC controller.

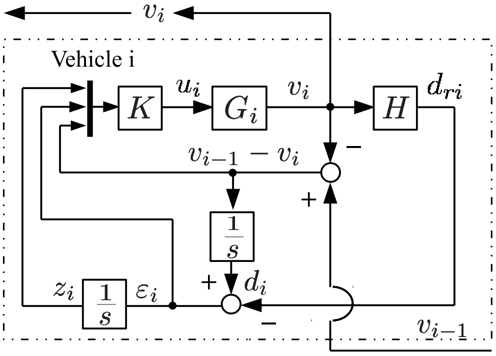


Fig. 3. Block diagram of ACC

B. Modeling Error Compensator

It is well known that STAVi's dynamic model is nonlinear [7]. Therefore, the acceleration and deceleration model represented as eq.(1) is strictly different from the plant. Besides, STAVi's parameters are changed according to driving situation. In particular, the STAVi's body weight is about 80[kg], also maximum driver's weight is assumed to be 80[kg]. Fluctuation of weight has a significant influence on the longitudinal control, because the driver's weight ratio against STAVi is larger than the ratio against car.

To design the platoon controller, it is difficult to obtain not only the STAVi's parameter but also precise bodily weight for every vehicle and patient. If the modeling error can be minimized, we design ACC parameters for nominal model regardless of various parameter changes. In this paper, a Modeling Error Compensator (MEC) is used to suppress the error of ACC [4].

Fig.4 shows the block diagram of MEC. In this figure, P and P_M represent the dynamics of STAVi and the reference model. The vehicle velocity v_i is the output of P, and v_{mi} is the output of P_M, where i denotes $i-th$ vehicle. C is the controller compensating the model error between P and P_M. In case the same characteristic between P and P_M is given, the feedback becomes invalid. On the other hand, in case of the different characteristic between P and P_M, control input works to minimize $v_{mi} - v_i$. By proposed compensator, it is expected that the input-output relation of P becomes close to that of P_M.

Here, the longitudinal reference model P_M is represented as follows;

$$P_M = \frac{v_{mi}}{u_i} = \frac{1}{\tau_{mi} s + 1} \ , \tag{4}$$

where τ_{mi} is time constant of reference model. C is PD type controller to compensate the model error.

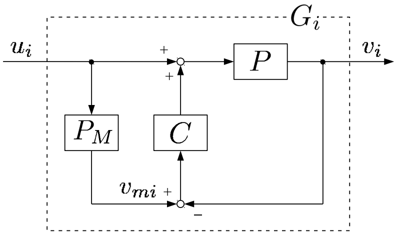


Fig. 4. Block diagram of Modeling Error Compensator

IV. DESIGN OF LONGITUDINAL CONTROL

Fig.5 shows block diagram of longitudinal control system of platoon driving. Left-side block is feedback gain of ACC for nominal model, and right-side block is STAVi compensated by MEC. In this section, the design method of desired time-headway T, reference model P_M, and feedback gain K are discussed.

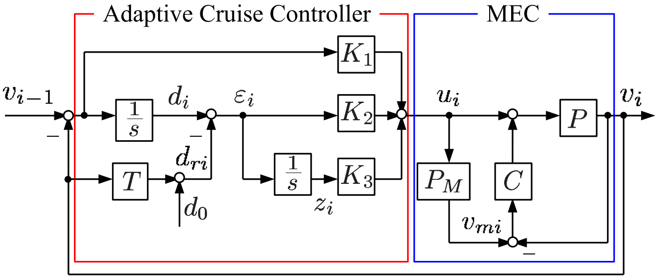
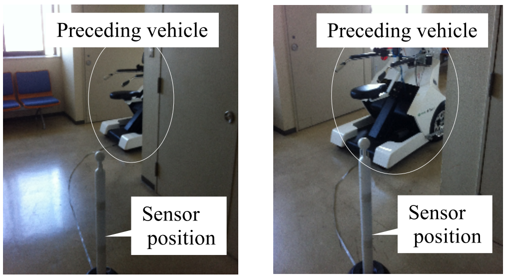


Fig. 5. Block diagram of platoon driving system

A. The desired inter-vehicle distance

It is easy to be string stable for platoon system if large desired time-headway T is given in eq.(2). As the large T gives long inter-vehicle distance, large T is not permitted for narrow indoor driving.

In the case of the platoon driving system, the preceding wheelchair disappears at the corner by the wall. This implies that inter-vehicle distance cannot be measured. Therefore, we determine appropriate time-headway T not to lose sight of preceding wheelchairs. The vision from following wheelchair is shown in Fig.6, when the following wheelchair is driven at about 2[km/h]. Fig.6(a) and (b) indicate inter-vehicle distance at $T = 3.0$[s] and 1.0[s]. In case of $T = 3.0$[s], the time-headway is sufficient large for stable driving, but preceding wheelchair disappears at the corner by the wall as shown in Fig.6(a). In case of $T = 1.0$[s], as the wheelchair does not disappear, the distance can be measured easily as shown in Fig.6(b). By preliminary experiments, we define the desired time-headway $T = 1.0$[s] and $d_0 = 1.0$[m], where the following vehicle's velocity is assumed 0.5[m/s] (2.0[km/h]).



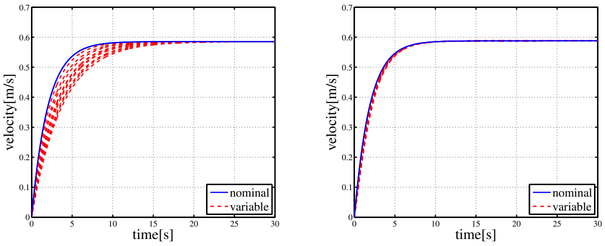
(a) $T = 3.0$[s] (b) $T = 1.0$[s]

Fig. 6. Setting of time-headway T

B. Longitudinal reference model with MEC

We show some simulation results to confirm the effectiveness of MEC for the variation of driver's weight [7]. STAVi's gross weight range is $M \in [80\ 160]$[kg]. To show the effectiveness of MEC, we examine the open loop response of STAVi, at first.

The wheelchair velocity without MEC under variation of gross weight is shown in Fig.7(a). The nominal model's weight is $M = 80$[kg] that means no passenger. The heavier the weight becomes, the larger the time constant will be. Fig.7(b) shows the velocity with MEC. Even thought the weight is changed, the model error is suppressed by MEC. As STAVi is regarded as the reference model P_M, ACC controller can be designed for the reference model.



(a) Without MEC (b) With MEC

Fig. 7. Velocity of STAVi perturbed by the weight change

C. Design of ACC controller

Platoon driving system is generally designed to satisfy string stability [8]. The string stable denotes that oscillation of inter-vehicle distance is not amplified upstream from d_{i-1} to d_i. When the following wheelchairs repeat acceleration/deceleration, the drivers feel uncomfortable due to the oscillations. For the reason, we should design the ACC gain not only to be string stable, but also to be oscillations-free.

The criterion of string stable is given as follows;

$$||SS(s)||_\infty \leq 1 \quad \forall \omega \ . \tag{5}$$

In case that $||SS(s)||_\infty \leq 1$ for all frequency, the platoon satisfy string stable. Here, $SS(s)$ is a transfer function from d_{i-1} to d_i assuming all time constant τ is identical.

$$SS(s) = \frac{d_i}{d_{i-1}} = \frac{K_1 s^2 + K_2 s + K_3}{\tau s^3 + K_a s^2 + K_b s + K_3} \tag{6}$$

where $K_a = 1 + TK_2 + K_1$, $K_b = TK_3 + K_2$.

The ACC feedback gains are characterized by root locus. The weight matrix is $Q = \mathrm{diag}[1\ 300\ 470]$, where state vector $x = [\dot{d}_i\ \varepsilon_i\ z_i]^T$. The weight r of input matrix is changed from 100 to 0.001. The root locus is shown in Fig.8. From eq.(6), $SS(s)$ has three poles and two zero points. If r is smaller, the poles are moved to arrow direction.

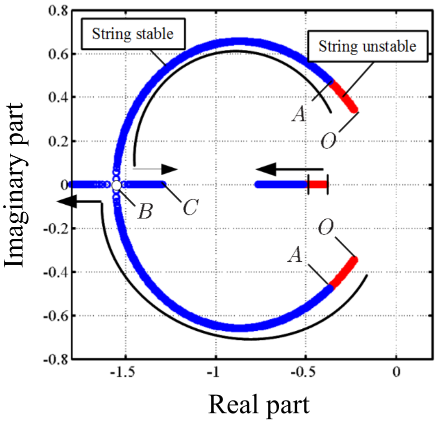
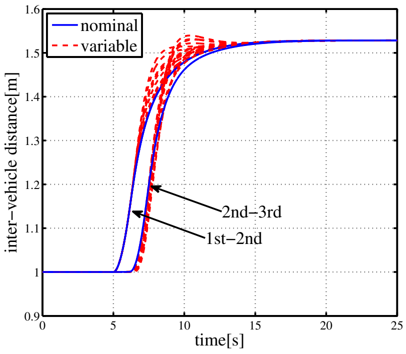


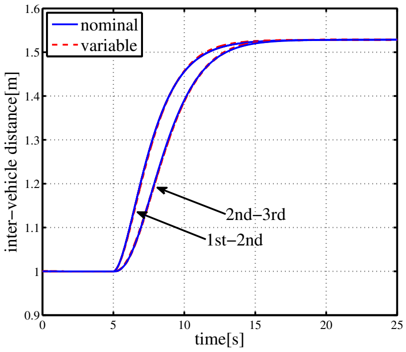
Fig. 8. Root locus of $SS(s)$

Platoon driving characteristics is changed according to poles location. When r is large value, poles are located on area $O-A$. Then, the wheelchairs are string unstable. When r is small value, poles are located on area $A-C$. Then, the wheelchairs become string stable. In particular, when r is smaller than 0.013, the oscillation of inter-vehicle distance doesn't arise because poles are located on real axis $B-C$. So, it is better to set r as smaller than 0.013 to be string stable. In this paper, we define $r = 0.01$ to suppress oscillation and obtain the feedback gain $[K_1\ K_2\ K_3] = [73.27\ 241.6\ 151.9]$.

We confirm effectiveness of the proposed platoon driving system by the simulation. The leading wheelchair starts driving at 5.0[s], after then the leading wheelchair drives at constant velocity 0.52[m/s]. The gross weight is changed as $M \in [80\ 160]$[kg]. Fig.9 (a) and (b) show inter-vehicle distance without and with MEC, respectively. Solid line and dash line are nominal and fluctuation of responses, respectively. When the weight is changed, inter-vehicle distance is amplified than nominal one. When the proposed controller is used, the overshoot is suppressed even though driver's weight changes. As a result, the inter-vehicle distance converges without oscillation.



(a) without MEC



(b)with MEC

Fig. 9. Simulation result of inter-vehicle distance

V. DESIGN OF LATERAL CONTROL

In this section, a practical CTH control along wheel track of preceding wheelchair is proposed to achieve a precise platoon driving.

A. *Traditional control based on target point following*

The target point following (TPF) is major method for lateral control [5] [9]. Fig.10 show a schematic diagram of TPF algorithm. When target point (x_p, y_p) is given, the desired trajectory (heavy line) is generated using third-order curve to drive smoothly.

It is well known that the platoon following error will be larger if the number of vehicles increases. Fig.11 and Fig.12 show experimental results of traditional TPF with ACC at corridor corner. In Fig.11, the maximum following error was 0.36[m] in corridor corner. Also the inter-vehicle distance between preceding and following wheelchairs is shown in Fig.12. Maximum inter-vehicle distance error was about 0.18[m] ($d_r = 1.55$[m]). However, inter-vehicle distance is not precise at the corner because the distance is measured by direct distance using Laser Range Finder (LRF). The issue is lack of accuracy for narrow indoor platoon driving. In this case, only one patient can be lead using traditional controller when corridor width is 2.0[m].

B. *CTH control algorithm along wheel track*

Generally, way points have been used at inflection point of the trajectory for automatic drive system [5]. In this paper, precise CTH control along wheel track of preceding wheelchair using way point generation is proposed. The concept of way point generation along wheel track is shown in Fig.13. The way point data detected by LRF are marked

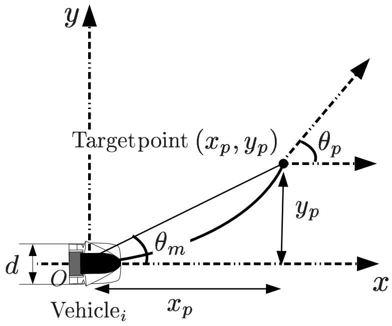


Fig. 10. Schematic diagram of TPF algorithm

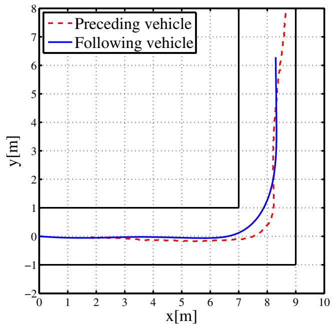


Fig. 11. Vehicle trajectory using traditional TPF algorithm

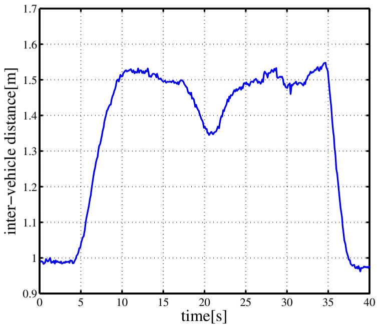


Fig. 12. Inter-vehicle distance using traditional ACC

by following wheelchair. The detail algorithm is omitted in this paper, but the way points are rotated according to yaw angle of following wheelchair. As the way points are marked within certain period (100[ms]), the target wheel track will be more precise in slow speed.

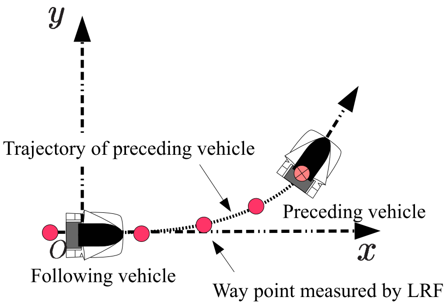


Fig. 13. Proposed time-headway tracking along wheel track

VI. EXPERIMENT OF PLATOON DRIVING USING STAVI

In this section, we show some experiments using STAVi. STAVi$\sharp$3 is the preceding wheelchair and STAVi$\sharp$2 is the following one. LRF (UTM-30LX) is mounted on following wheelchair to measure the relative position. The relative position among wheelchairs are estimated by odometry method obtained by encoders [6].

A. Experiment of driving straight corridor

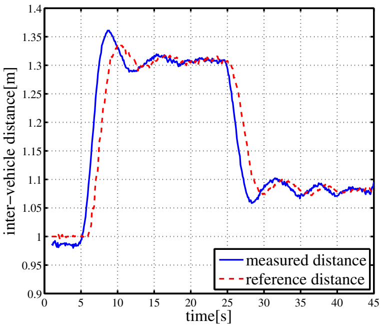
The effectiveness of proposed control system is confirmed by driving experiment. The preceding wheelchair starts driving at 5[s], and keeps the constant velocity 0.3[m/s] until 25[s]. And the preceding one decelerates to about 0.1[m/s]. Table I shows control parameters.

TABLE I

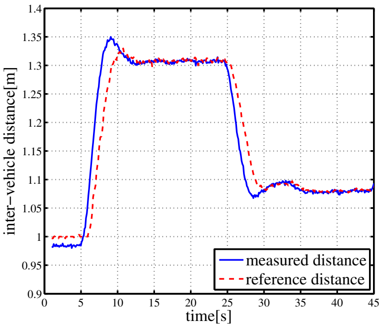
EXPERIMENTAL PARAMETERS

Name	Symbol	Value
Sampling time	Δt	0.1[s]
Time constant of P_M	τ_M	0.5
Desired time-headway	T	1.0 [s]
Standstill distance	d_0	1.0 [m]
Gain of ACC	$[K_1\ K_2\ K_3]$	[73.27 241.6 151.9]
Gain of MEC	$[C_P\ C_D]$	[240 35]

Fig.14 shows inter-vehicle distance. The desired inter-vehicle distance was 1.3 [m]. In Fig.14(a), when the preceding wheelchair accelerated or decelerated, the overshoot was observed and following wheelchair velocity converges with oscillation. In this case, the string stability was not guaranteed. In Fig.14(b), the oscillation of inter-vehicle distance was suppressed stably using proposed method. Here, ACC gain was adjusted for $M = 80$[kg] without passenger. From the experiment, the parameter variation by passenger's weight was suppressed by MEC.



(a) Inter-vehicle distance without MEC



(b) Inter-vehicle distance with MEC

Fig. 14. Experimental evaluation on straight corridor

B. Experiment of following error at corridor corner

We show the driving experiment to turn off at the corner of corridor. The preceding wheelchair accelerated until 0.5[m/s]. The corridor width is 2.0[m] and STAVi width is 0.7[m]. The preceding wheelchair turns off at the 90[deg] corner with constant velocity.

The following wheelchair's velocity is controlled by ACC with MEC. Also, the inter-vehicular distance is controlled by

Fig. 15. Driving experiment at corridor corner

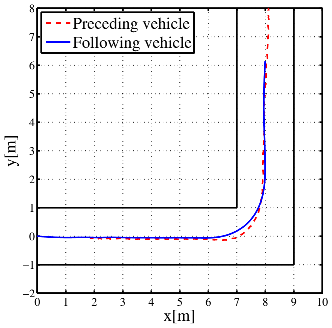


Fig. 16. Experiment of vehicle trajectory

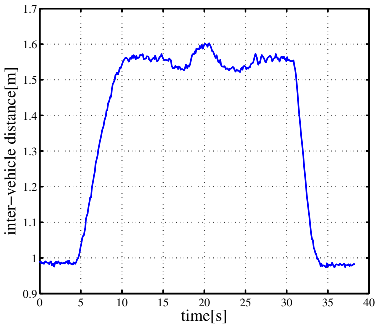


Fig. 17. Experiment of Inter-vehicle distance

proposed method along wheel track of preceding wheelchair. The wheelchair can follow measured way point by proposed algorithm. Fig.15 is the condition of a driving experiment at corridor corner. The curvature radius of reference trajectory at corridor corner is 1.0[m].

Fig.16 is an experimental trajectory. Maximum trajectory error between preceding and following wheelchair was suppressed 30.5% comparing one of traditional TPF method. By using proposed controller, it is expected that five patients can be led by platoon leader. Integral Absolute Error (IAE) is evaluated for precise platoon driving at the corner. IAE is defined as

$$IAE = \int_{t_1}^{t_2} \sqrt{(x_p - x_f)^2 + (y_p - y_f)^2 dt} \qquad (7)$$

where (x_p, y_p) and (x_f, y_f) are position of preceding and one of following wheelchair. For evaluation, we set $[t_1, t_2] = [11, 34]$[s], which is defined as constant velocity interval. Comparing Fig.11 and Fig.16, the error of proposed method was smaller than one of TPF. The IAE of proposed method was improved to 13.52 (12.8%) although the IAE of traditional TPF was 105.6.

TABLE II

LARGEST ERROR IN EXPERIMENT (CORRIDOR WIDTH:2.0[M])

Type	Max error at corner	Error of inter -vehicle distance	Number of party
Traditional	0.36[m]	0.18 [m]	2-vehicles
Proposed	0.11[m]	0.05 [m]	6-vehicles

Fig.17 shows experimental inter-vehicle distance. The inter-vehicle distance error was improved from 0.18[m] to 0.05[m] where time-headway set as $T = 1.0$[s] (inter-vehicle distance 1.57[m]). Table II summarized maximum errors at corner of corridor.

VII. CONCLUSION

In this paper, we proposed indoor platoon driving of electric wheelchair with MEC along wheel track of preceding vehicle. In this experiment, the leading number of wheelchairs was six vehicles included leader. The advantage of our method is implemented easily for parameter variation of the platoon system even though this system uses odometry method. By suppressing the model error using MEC, comfortable control system can be realized without oscillation of velocity. Also, the lateral controller was based on CTH control along wheel track of preceding wheelchair. The way points were generated considering the relative position of wheelchairs. The effectiveness of proposed control system was evaluated by experiments at narrow corridor.

We designed the MEC for longitudinal controller, however, the MEC for lateral motion has not been considered yet. For precise following, the design of nominal model considering longitudinal and lateral controllers, application of corporative ACC and localization of platoon are future works.

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