Development of Trajectory Generator Program for Path Planning of Industrial Overhead Cranes

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***Abstract*— According to the complex dynamic of an overhead crane, developing a payload path planning is a labored task for inexperienced operators. This paper shows the developing tool for 3D payload path planning of industrial overhead cranes dominated by speed control mode. The velocity trajectory generator program based on user interface (UI) was developed using the App Designer in MATLAB. The trajectories are based on the cubic polynomial trajectory and the adaptive command smoother. The cubic polynomial trajectory is used for generating the smoothed path of each waypoint while the payload sway suppression is handled by the smoother. By this concept, the crane moves through the sequentially given waypoints according to given waypoint constraints such as velocity and time. In the program, the user must define the desired waypoint coordinates while the velocity points and time points can be automatically obtained by the program. Furthermore, the program can visualize the workspace and the payload path prediction in 2D and 3D as well as the plot of velocity trajectories in the three axes. The travelling path information is also provided to evaluate the desired path before the velocity trajectories are exported.**

Keywords—overhead crane, path planning, user interface

I. INTRODUCTION

A typical overhead crane is controlled by an operator using a pendant push button to manipulate a payload in a workspace. Basically, a payload is normally considered as a simple pendulum. It is lifted by a hoist attached under a bridge and a trolley. The trolley moves along the bridge length for the left and right directions. Finally, the bridge moves forward and backward directions. For the drive system, an overhead crane is driven by inverters and induction motors that are installed to all three axes resulting in overhead crane moving in three dimensions. The overhead crane components are a minimal concept yet effective design that yields overhead cranes a popular mechanism. However, any movements of the overhead unit naturally swing the payload. Besides, the misaligned position between the hoist and the payload when the hoisting operation is performed causes payload sways as well. Therefore, the main problem is payload oscillation, which may initiate accidents in any operations. The two main control perspectives were usually used to suppress the payload sway: feedforward control and feedback control. For the feedforward control, input shaping techniques were popularly used for the industrial overhead crane [1] [2]. Beside the input shaping, the command smoother was recently proposed and demonstrated superior performances compared to an input shaping [3]. The feedforward techniques can suppress the payload sway of overhead crane due to its translational motion, but it cannot work under the presence of uncertainty. On the contrary, the feedback control can suppress the payload sway even if the crane is in the presence of uncertainty. For the feedback control, the gain scheduling PID was used to suppress the payload sway [4], the sliding mode control [5], and intelligent controls [6] [7]. Recently, a combined feedforward and feedback control as the model reference form was proposed. The combined control can maintain the main characters of the feedforward, yet perform disturbance rejection [8].

As the global productivity in many industries is increasing, using an operator to control a conventional overhead crane may not suffice for today industries' demands. Therefore, overhead cranes need to be more automated. An automated overhead crane can move a payload to a target faster than an operator who is familiar with the crane. In other words, an operator must take some time to decide their reaction, while an automated overhead crane moves the payload to a desired position by means of computational technology that the payload is moved along the given path and the desired payload dynamics. In terms of path planning, the planned path is not only a drawn line in workspace but also contains the dynamic constraints such as velocity and time of each waypoint in the planned path. As described, an automated overhead crane transports the payload without demanding operator skills, resulting in less time consumption in a transporting process.

Several researches were done for the automatic path planning using several approaches such as online or offline path planning on the known or unknown workspace. A trajectory was frequently calculated from the optimization based on the dynamic model of the crane where the travelling time between these waypoints is minimized. For instance, Minh Nhat Vu, A Lobe, F Beck, and T Weingartshofer [9] presented the novel work that the crane can be automatically moves the payload to the target, even though the position of the target is changing in the known workspace. So that, the online trajectory was proposed. Hongjie Zhu, Huimin Ouyang, and Huan Xi [10] used the ninth order polynomial as the trajectory generator to smooth the path between two waypoints for the obstacle avoidance system in the rotary crane application and a known workspace. To parameterize the trajectory equation, the optimization problem was set to minimize the travelling time while the given dynamic constraints of the crane are satisfied. Waikoonvet J, Suksabai N, and Chuckpaiwong I [11] proposed the method for the collision-free path of the overhead crane using modified ant colony algorithm and third-order polynomial trajectory generator. He Chen, Yongchun Fang, and Ning Sun [12] proposed the novel time-optimal trajectory planning method using the b-spline trajectory generator with the degree 6 for the positioning and sway suppression. Unlike the conventional version of the trajectory that is parameterized by the waypoint and time, the proposed one takes the dynamics of the overhead crane into account such as the sway angle and acceleration.

The reviewed approaches are certainly difficult because the path and dynamic constraints are automatically obtained by a proposed algorithm. Most of the research was done based on numerical simulation or lab-scale overhead cranes where the specialists were working for. To develop a path planning of a typical overhead crane that any operators can work with, a simpler approach must be considered.

This paper presents the path planning in 3D workspace of an industrial overhead crane. The trajectory generator as the user interface (UI) program is presented. The program generates the information (the velocity trajectory) that can be applied to the real industrial overhead crane operated under speed control mode. The trajectory is the convolution between the cubic polynomial trajectory and the command smoother in the adaptive version. In the program, the path can be visualized by manually defining the waypoint coordinates in 3D workspace where the velocity and time of each waypoint can be automatically obtained by the program. The ability of workspace visualization of the program helps the user to plan the design path for manual collision avoidance. The user can visualize the payload path in the workspace taking the payload sway into account.

II. METHOD

A. The trajectory with capability of sway supresssion

The cubic polynomial trajectory and the command smoother are used as the trajectory generator. The velocity trajectories from cubic polynomial are convoluted by the command smoother to be the smoothed velocity trajectories. It is expected to move overhead crane in the speed control mode. So that, the smoothed velocity trajectories induce no payload sway. Figure 1 shows the smoother used in the path control application. In the figure, the smoother shapes the trajectory ($\dot{P}_d$) to the smoothed trajectory ($\dot{P}_{sm}$) before sending to the 3D overhead crane. The crane outputs sway angles (θ_x, θ_y) and positions (P). The detailed concept of the command smoother can be found in [3]. The model of 3D overhead crane is the combination of driven unit model and the simple pendulum model where the driven unit model is an empirical model, already studied and presented in [13]. In brief, the command smoother is a transfer function whose zeros are placed at the same locations of the oscillated poles of the overhead crane model and whose poles are selected for reducing payload sway and acquiring fast transient response. As the results, the oscillated poles of the crane will be cancelled, and poles of the command smoother will be the new poles of the control system, resulting no payload sway.

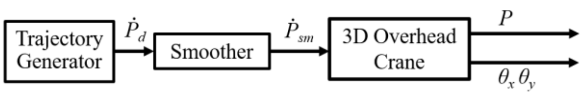


Fig. 1 The payload path from feedforward control

B. Velocity point generation

When the cubic polynomial trajectory is used for generating the 3D path of overhead crane, seven parameters of each waypoint is needed including the three coordinates and three velocities and a desired time. This section will describe how each velocity point can be automatically obtained. The magnitude and direction of each velocity of the 3 axes are not defined by the user but the program.

For the velocity points, the program will only ask for a percent speed of the payload for each point. It means that the magnitude and direction of each velocity point in 3 axes are automatically generated. Figure 2 demonstrates the blue arrow vector of the velocity of the waypoint n where the superscribe n is a waypoint number, x_d and y_d are the desired positions of the waypoint, and $\dot{x}_d$ and $\dot{y}_d$ are the calculated desired velocity of the waypoint. The resultant vector direction of the velocity point n is calculated by the position of the waypoints before and after as shown in the figure. The resultant vector magnitude is maximized under the velocity limits of the crane.

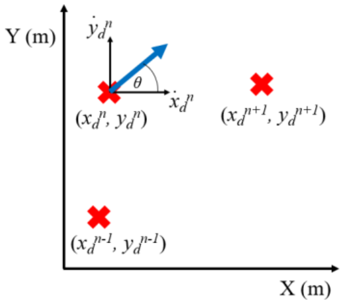


Fig. 2 Example of automatically defined velocity point

C. Time point generation

This subsection describes how the time points are automatically generated. The program procedure that is used for calculating each time point is shown in Fig 3. The program starts with the initializing process where every time point in the desired waypoints is set to zero. Then, the first segment, which is the smoothed path between the first and second waypoints are considered. In the program, the time point at the second waypoint is gradually increased by a small value, then the cubic polynomial trajectory function in the MATLAB program is then used to calculate the trajectory of the first segment. As the result of calculation, if there is any points in the velocity or acceleration trajectories profile that exceed the limits, the time point of the second waypoint is gradually increased, then the cubic polynomial trajectory function is recalculated. The gradually adding the time point process will be iteratively executed until every point in the velocity or acceleration trajectory profiles is within the limit. Then, the first segment is done. The process for the second segment will be then executed in the same manner and so on.

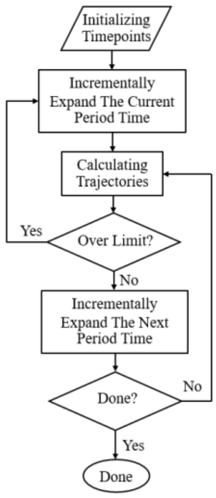


Fig. 3 The flowchart of time point calculation program

D. The adaptive command smoother

In the trajectory generator program, the adaptive version of the command smoother is used to support the large parameter variations resulted by the difference of chain length from desired waypoints. The adaptive command smoother convolutes the velocity trajectories of the 3 axes provided by the cubic polynomial trajectory. The adaptive command smoother is a linear parameter varying system (LPV). The poles and zeros are changed according to the changed adaptive parameters, which are the acceleration and deceleration limits and chain length. More information can be found in [3].

Unlike the previous results that all parameters are constant, the adaptive parameters are used in this paper. The optimization of the command smoother parameters was done for 10 cases where the main parameters are varied. In this study, the same optimization will be again conducted to synthesize the smoother parameters for more cases. The results will be used in the development of the adaptive of command smoother using the two-dimensional interpolation technique.

E. Program procedure

This section describes the program procedure for generating the trajectories for 3D overhead crane. The flowchart in Fig. 4 shows each step of the program from the beginning to the end. The output of the program is arrays of velocity trajectories in 3 axes, ready to transfer to the PLC for the experiment. The flowchart is described as follows:

For the initializing data block, the waypoints information must be defined. The waypoints information includes desired waypoint coordinates in 3D, a desired percent speed of each point, and a desired time of each point. The desired waypoint coordinates include the desired position of trolley in X and Y axes, and hoist length in meter unit. The desired percent speed of each point can be defined from 0 to 1. Note that, the desired percent speed is not velocity information that contain magnitude and direction. The desired time of each point can be defined in second unit. This waypoint information can be defined using the program interface or importing function of the program. Besides, the crane parameters must be defined as well, which are the maximum velocities of the 3 axes, the maximum acceleration of both X and Y axes, and the maximum hoisting length.

To draw the map and waypoints, users can import 3D file of the workspace, which is an .stl file to visualize the map and obstacles in the workspace as well as the defined waypoints in Microsoft Excel .xlsx format. After importing the 3D map, users must prove and correct the data to ensure that the map and the waypoints are agreeable according to the desired payload motion.

After correcting data and before executing the trajectory calculation, users must select the travelling time options. First, the user will have the option to let the program calculate the optimal time of each point or manually define the time points by themselves. Second, the user must select the trip option, which is either one-way or return. The one-way option means that the payload moves from one point to another along the given waypoints. The return option means the payload moves from one point to another and returns to the defined starting point. Furthermore, the delay time at the starting point and the destination can be defined when the return option is selected. The crane will stop the payload movement due to the defined delay time. It is developed for the purpose that the operator can work with the payload in routine operation.

After the travelling option is made, the program is ready to generate trajectories. When the program is executed, it calculates the trajectories based on the cubic polynomial and the adaptive command smoother. The calculated trajectories are sent to the overhead crane model. The payload positions from the model are plotted as the desired path in 2D and 3D as well as the velocity trajectories with respect to time. The user must evaluate the payload path to avoid the payload collision using the 3D map. If the results are satisfied, the user can export the trajectories of the 3 axes based on the .xlsx file. The time step of the desired velocities trajectories is 20 milliseconds.

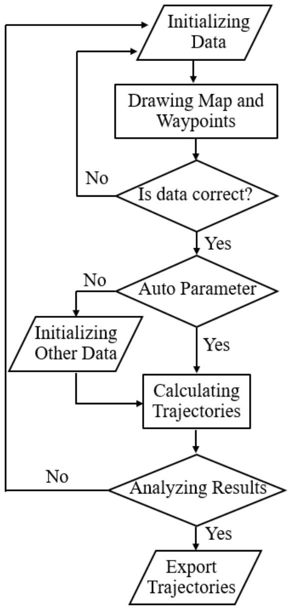


Fig. 4 The flowchart of the trajectory generator program

III. RESULTS

This section will demonstrate the proposed program. The proposed program contains groups of three tabs including the Setting tab, the 3D tab, and the Trajectories tab shown in Fig. 7, Fig. 8, and Fig. 9, respectively. In addition, the toolbar located at the top of the program is available for importing and exporting data by clicking on the File menu shown in Fig 5. The demonstration will begin with importing and end with exporting. How to initialize the program, execute the program, and evaluate the program will be shown as well.

Fig. 5 shows the File menu that users can import both 3D map of a workspace and unlimited waypoints using the specific file name extension. Users can export both cubic polynomial trajectory and smoother trajectory (cubic polynomial trajectory + smoother trajectory) in the specific file name extension. The file name extension of the 3D map must be .stl and the file name extension for importing waypoints data, exporting cubic data, and exporting smoother must be .xlsx with the specific formation. 3D map could be sketched by any computer aided design (CAD) software that can export the .stl file of the sketched 3D map. The Microsoft Excel software is used for preparing waypoint data and receiving the exported data.

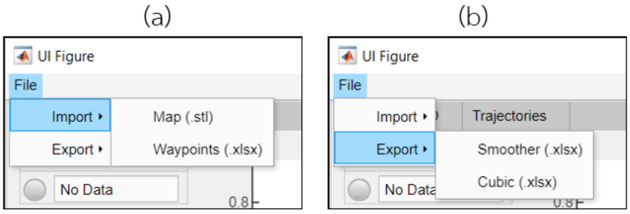
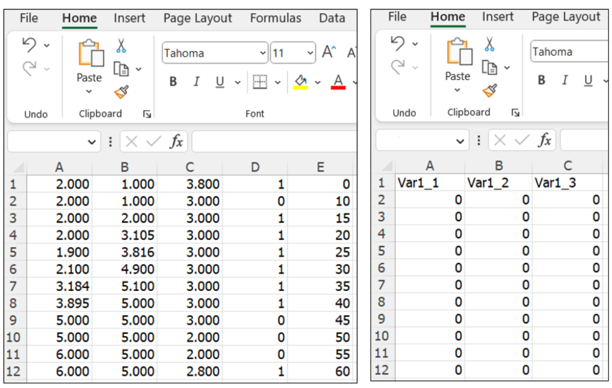


Fig. 5 The program user interface showing the File menu

The waypoint data must be prepared as shown in Fig. 6 (a) where the columns A, B, and C are for waypoint coordinates in X, Y, and hoist axis in meter unit, respectively. The columns D and E are for the percent speeds from 0 to 1 and time points, in second unit, respectively. Each row in the Microsoft Excel file is for each waypoint information strictly started from the first row. On other words, the cells A1, B1, C1, D1 and E1 are for the first waypoint, the cells A2, B2, C2, D2 and E2 are for the second waypoint, and so on. Fig. 6 (b) shows the format of the exported velocity trajectory in m/s unit where column A, B, and C are the velocity trajectory of X, Y, and hoist axis, respectively. Each row in the Microsoft Excel file separates the velocity data for 20 milliseconds.


(a)

	A	B	C	D	E
1	2.000	1.000	3.800	1	0
2	2.000	1.000	3.000	0	10
3	2.000	2.000	3.000	1	15
4	2.000	3.105	3.000	1	20
5	1.900	3.816	3.000	1	25
6	2.100	4.900	3.000	1	30
7	3.184	5.100	3.000	1	35
8	3.895	5.000	3.000	1	40
9	5.000	5.000	3.000	0	45
10	5.000	5.000	2.000	0	50
11	6.000	5.000	2.000	0	55
12	6.000	5.000	2.800	1	60

(b)

	A	B	C
1	Var1_1	Var1_2	Var1_3
2	0	0	0
3	0	0	0
4	0	0	0
5	0	0	0
6	0	0	0
7	0	0	0
8	0	0	0
9	0	0	0
10	0	0	0
11	0	0	0
12	0	0	0

Fig. 6 The format of an .xlsx file: (a) the waypoint data and (b) the exported velocity trajectory data

Fig. 7 shows the setting page where the crane parameters and the program options that must be defined. In this page, several panels and buttons are displayed as the following.

• First, status panel reports the program status that the display may report the words: No data, Ready to Run, Done, and Check the Arrays. The lamp status according to the reported word is also shown as grey color, yellow color, green color, and red color, respectively.

• Second, the crane parameters must be defined in Crane Parameters panel including the maximum velocities of the 3 axes, maximum acceleration of both X and Y axes, and maximum hoisting length.

• Third, the option for defining the time point is in the Time Point Generation panel. Users must select one of the options: Auto or Manual. If Auto is selected, the program calculates the optimal time for each waypoint that the method was presented in previous section. If Manual is selected, the program used for time point data from the imported file shown in Fig. 6 (a), column E. In addition, all percent speeds defined in column D can be proportionally increased or decreased by the defined gain in this panel, which is the "Perc. Speed".

• Fourth, the options for the payload travelling in workspace must be defined in the Travelling Options panel. Users must select one of the options: One-Way or Return. If One-Way is selected, the crane moves the payload from the first waypoint to the last waypoint. If Return is selected, the crane moves the payload from the first waypoint to the last waypoint and returns the payload from the last waypoint to the first waypoint. For the Return option, the crane stops the payload movement by the given delay time at both the first and the last waypoint.

• Fifth, for the Run and Clear buttons, if the program status reports "Ready to Run" and the lamp turns yellow, users can click the Run button to generate the velocity trajectory. Contrarily, if the program status reports "Check the Arrays" and the lamp turns red, users must click the Clear button to remove the imported waypoint data. Usually, there was some data missing. Users must correct the data and import it again.

• Sixth, right after the 3D map and the waypoint data were imported, the plot titled as "Workspace (Top View)" visualizes the workspace in 2D (X and Y axis) as well as the waypoint coordinates. When the Run button is clicked, the plot will draw the payload path using the blue line. However, users have the option to edit the waypoints data directly on the Manual Setting Waypoints Information panel. Each waypoint data is separated by a space (hitting the spacebar once). Certainly, the number of each data must be the same to each other. Clear button is used to remove the waypoints data.

• Finally, the 3D tab is shown in Fig. 8 that visualizes the workspace in the 3D as well as the waypoints and the desired payload path. The Trajectories tab is shown in Fig. 9 that velocity trajectories of three axes are plotted. In this tab, the travelling information such as total distance of each axis, the travelled payload distance, and the total travelling time are displayed.

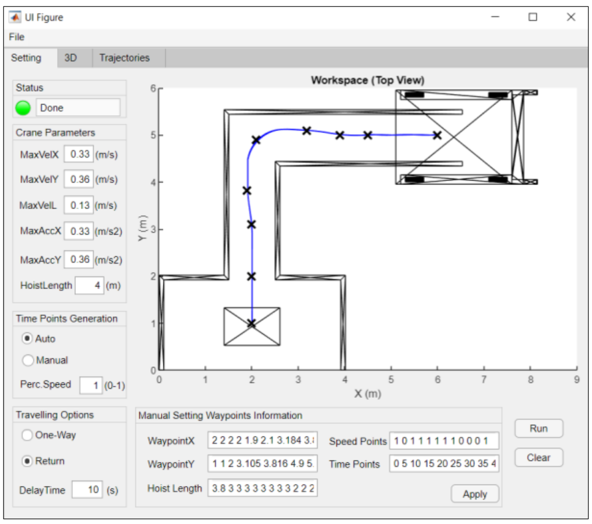


Fig. 7 Program user interface showing the Setting tab

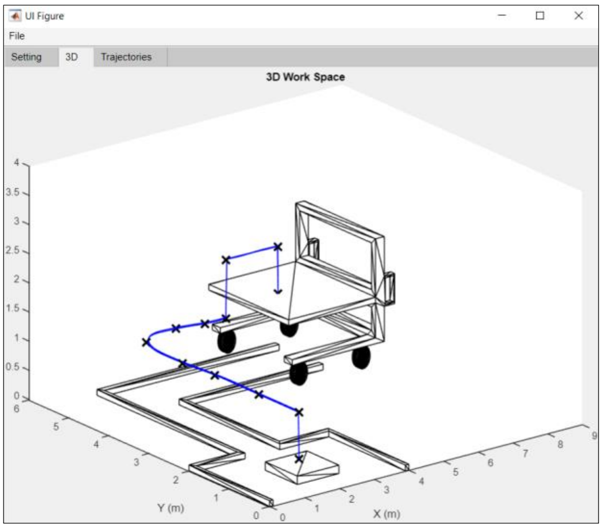


Fig. 8 The program user interface showing the 3D tab

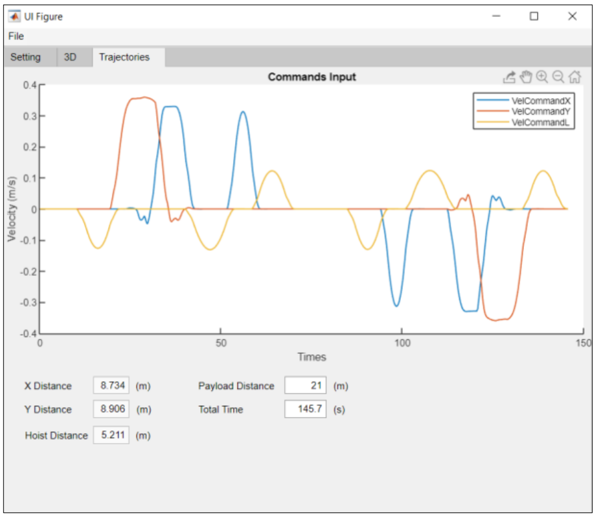


Fig. 9 The program user interface showing the plot of trajectories in Trajectory tab

IV. Conclusions and Discussions

A. Conclusions

To generate the velocity trajectory in the 3D path control, the user interface (UI) program was developed in this study. The trajectory is the combination of the cubic polynomial and the adaptive command smoother. The smoothed path between the given waypoints is mainly obtained by the cubic polynomial while payload sway is suppressed by the effect of the adaptive command smoother. The program can visualize the workspace in 2D and 3D as well as the generated path from the given waypoints. After the trajectory is calculated and the path is visualized, the trajectory can be exported as the .xlsx format, which is suitable for the industrial overhead crane operated under speed control mode.

B. Discussions

Although the experiment has not been conducted to verify the trajectory in the path planning task, discussions on using this trajectory in the real overhead crane environment will be provided here.

- Three velocity trajectories that are generated by both cubic polynomial and the command smoother remain under the limitations of velocity and acceleration of the overhead crane. The crane would precisely follow the trajectory according to its speed control mode, if the motors and inverters are sufficiently designed to cover all the payload mass.
- The payload would move toward the trolley by the effect of the command smoother that cancels the payload oscillation in horizontal motion. Therefore, if the payload always stays under the trolley the payload would move along the desired path.
- The crane could not follow the trajectories only when the size of the motors and inverters are not enough to handle the large payload mass.
- Finally, the payload will deviate from the desired path if there are any disturbances that come in because of the limitation of feedforward control.

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