Workbench Control System Design Based on Mecanum Wheel

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Abstract. The Mecanum wheel gains the particular interests in the field of robot, vehicle and workbench due to the capabilities of moving toward, sideway, rotation and combination of other motion pattern. This report details the progress of designing and building an omni-wheel robot control system which is controlled by Programmable Logic Controller (PLC) to achieve the ability of instantaneous motion in any direction with 4 coupled Mecanum wheels involved. A simulative control program has been developed to fulfill the function of line motion. Additionally, several advanced control methods have been reviewed, such as FPGA, NLP and TLC, which can be helpful in the future modification and improvement.

1. Introduction

The omni-directional wheel is implemented to transmit different parts of force into a total force vector to longitudinal (forwards or backwards), lateral (left or right shift) and other desired rotary (angled translation). It had been widely used in the fields of vehicle and robot and the very most basic dynamic and kinematic models had been summarized over the past twenty years [1]. However, most of the previous research results mainly focus on small dimension and model with less number degree of freedom, such as Asama et al. aimed to develop an omni-directional mobile robot, using a decoupling drive mechanism to control the motion for three degrees of freedom by three correspondent actuators in a decoupled manner in 1995 [2]. What’s more, Diegel et al. indicated the comparison of conventional wheel designs and special universal wheels [3]. Therefore, a study for the omni-directional mobile workbench with steel frame structure and full mobility has been proposed. It uses the programmable logic controller as the main control means, combined with the Pulse-Width Modulation of the motor output, to achieve the effect of flexible mobile movement. In addition, this paper also compares various types of control methods as reference for the improvement and optimization of the system in the future.

2. Design methods

2.1. Mechanical components selection

In this paper, 8 Mecanum wheels are selected to form the 4 paired distribution of coupled wheels. The Mecanum wheel was initially invited by Ilon [4]. The wheel geometry can be seen in Figure 1 below. The outline of the omni-directional wheel is circular by the shaped of rollers. If we cut a cylinder with a plane angled at $\gamma$, in this case $\gamma=45^\circ$ for Mecanum wheels. With analytic geometry and dynamics analysis if the roller length, $L_r$, is much smaller than the wheel external radius, $R$, then the roller shape...
could be approximated with a circle arc having $2R$ as radius. During the actual use process, in order to get a circular outline for the wheel, the minimum number of rollers should not be less than 8 [5].

![Figure 1. Wheel parameter.](image)

Two sets of 10 inches Mecanum wheel have been selected. This set of four wheels includes two right wheels and two left wheels. These wheels are assembled with 12 rollers per wheel. Each roller is a heavy-duty wheel itself, with 2 steel GGB bushings riding on a 1/2” aluminum axle. These axles and rollers are sandwiched between two 0.125” thick aluminum plates. The rollers are made of gray SBR rubber, with 80A durometer.

According to the general calculation of total power required, four 350W DC motor have been selected, with 24V nominal voltages and 15A current when fully loaded. For this reason, eight 12V lead-acid batteries are purchased as well, connecting with four groups of parallel connection. A set of spring damper has been used to reduce vibrations and oscillations when uneven ground condition is encountered. Additionally, steel driven shaft and connective ring have been built for the simultaneous movement between paired omni-wheels. The final assembly of the table-like robot with 8 Mecanum wheels is shown in Figure 2.

![Figure 2. Final assembly of mechanical hardware.](image)

2.2. Control system design

PLC is a digital processor used for automation of electromechanical processes. Unlike general-purpose controller [6], the PLC is designed for multiple inputs and output arrangements, extended temperature ranges, immunity to electrical noise and resistance to vibration and impact. In this project, the PLC could be acting as the importer and processor both simultaneously. This can be achieved because the robot can be started or stopped by the button on the control board and the motor rotating direction can
be calculated based on the routines downloaded in the PLC. Then PLC transfers the signals to motor
driver box and the chips in the box can output the PWM values to motors.

There are six buttons used which can achieve the functionality of whole system. They are start/stop,
reset, forward, backward, right and left and are all push buttons with latch, except the reset button.
Therefore every motion of instruction can only be executed individually, meaning that the PLC cannot
execute other three direction movement if the forward button is pressed. The advantage of this kind of
setting is that the amount of programming is small and it can avoid frequent positive inversion and
extend the service life of the motor. While in some special occasions, the efficiency of system is not
very high due to the motion decomposition when moving with angle. When the reset button is pressed,
the PLC will run the initialization program, all the tags or data stored in the memory of the controller
will be cleared.

For the safety concern when the motor is operating, a safe mode test function will be implemented.
This function only allows the motor to drive 5 seconds and then stop. It can be easily achieved by
using the timer control in PLC programs. After 5 seconds, the control box will output the PWM
signals at 0 percentages which means the motor is stopped. The only way to restart to movement is
pressing the reset button, which can initialize the program and eliminate the memory flags on PLC
chip.

Pulse Width Modulation is a process of digital coding to analog signal. By using the high
resolution counter, the duty cycle of the square wave is modulated to encode the level of a specific
analog signal. The signal is still digital form cause at any given moment, the full magnitude of the DC
power supply is either full (ON) or free (OFF). In the case, voltage or current source is applied to a
simulated load on a repetitive pulse sequence, which is connected or disconnected. The effect achieved
is very similar to the traditional digital analog converter (DAC), but the PWM technology is more
suitable for the case due to the consideration of the price and the motor type used in this paper. The
control sequence for a forward driving example can be seen in Figure 3.

Four VNH3SP30 motor driver chips are used to drive the four motors independently, labeling 1 to
4 sequentially. For the convenience of test condition and operation test, a control box was made to
integrate all the components of motor driver by the connection of two optoisolators in couple for one
control card (see Figure 4). It has four input interfaces for PLC signals transportation and one power
switch button, also four channels of outputs have been set with serial cable which could connect to
motors directly.

![Figure 3. Driving forward flow chat.](image-url)
3. Discussion & conclusions

3.1. Fuzzy control
Fuzzy control has been used to explain the behavior of an unknown system described by a set of numerical data. Wong et al. intends to design a fuzzy system to control an omni-directional mobile robot based on Genetic Algorithms method which can automatically generate fuzzy sets [7]. The prototype consists of three omni-wheels which located as an equilateral triangle and their rotation axes intersect at the center O of the chassis. When the coordinate frame is set fixed on the world plane, we can derive the inverse Jacobian matrix for this mobile system. Based on the kinematic model and the relationship between three inputs and three outputs, the rule base could be established, the triangular-shaped membership function can be determined accordingly, as shown in Figure 5. Seven subsections indicate the region of negative big (NB), negative medium (NM), negative small (NS), zero (ZE), positive small (PS), positive medium (PM) and positive big (PB). Although system can be subdivided into more parts, it will lead to a huge library of rules, the amount of data showed geometric growth.

It should be noted that the pulse waveform width (PWM) technology itself is a type of fuzzy control. But the PWM output is dominated by square wave form, which is only 0 or 1, which is different from the home function of Figure 5. If the motor speed needs to be changed, the voltages of input, feedback and output should be sampled and the duty cycle is calculated in real time.

3.2. Field Programmable Gate Array
Although the membership function seems sophisticated and tedious with a number of unknown parameters, they are quite detailed for the system in a very single motion. The value of these unknown parameters can be derived by an appropriate fitness function by the Field Programmable Gate Array (FPGA) chip involvement using Genetic Algorithm (GA). The GA method is a search heuristic which solutions better suited to the evaluation will have a greater chance of survival and offspring producing. It could extract the numerical data directly from function approximation and terminate when either a maximum number of generations has been produced, or a satisfactory fitness level has been reached.
for the population. Actuality, the combination of GA method and fuzzy logic control had been really in progress. It can be used to enhance the searching ability greatly of system movement towards optimal solution state in static and dynamic environment [8].

Hashemi et al. introduced a novel PI-fuzzy path planner for a linear discrete dynamics model of omni-directional mobile robot to satisfy planning prerequisites and prevent slippage with the implementation of velocity and acceleration filters [9]. Compared with the normal PID control method, the discrete-time linear quadratic tracking controller was used to provide an optimal solution to minimize the differences between the reference trajectory and the system output.

In fact, FPGA technology can also produce PWM rectangular pulse wave through a certain counter and comparator. In one process, by using the register to save the PWM cycle parameters, in the system clock driven by self plus, until the condition is satisfied to reset to 0, complete a PWM cycle. In another process, the PWM pulse width is controlled by comparing the register and the pulse width parameter. This method can achieve a better realization of the PWM signal, while it does not have a very good independence when the multi signal is required to appear at the same time.

3.3. Trajectory Linearization Control
Liu et al. improved a Trajectory Linearization control (TLC) method to fulfill the requirement of a nonlinear robot dynamic model [10]. It can achieve robust stability and performance along the trajectory without interpolating controller gains by combining a nonlinear dynamic inversion and a linear time-varying regulator. The TLC controller structure can be seen in Figure 6. It employed two loops architecture instead of dynamic inversion of the robot kinematics, based on the time-scale separation principle and singular perturbation theory. Following the body rate command from the outer-loop, in which the robot position is adjusted associated with desired trajectory, the inner-loop outputs the applied voltage on each motor subsequently.

Additionally, with the cooperation of onboard sensor and the vision system data, the model provides accurate and reliable position and orientation measurements. A nonlinear Kalman filter method is employed to linearize the nonlinear robot kinematics by using the nominal trajectory based on the outer-loop controller pseudo-inverse [11]. What's more, if the PMW method is applied to the control method, the abnormal value can be eliminated effectively, and the measuring range can be greatly reduced.

3.4. Nonlinear Programming
The time-optimal control is a method which considers the movement between two positions in the minimum time as the priority. Normally, the solution leads to the utilization the complicated mathematical theory of Pontryagin’s Minimum Principle (PMP) due to its highly nonlinear characteristic. However, Fu, Ko & Wu designed a nonlinear programming (NLP) methods which fixed the number of control steps while set the sampling period as a variable to minimize the optimization process based on a three-wheeled omni-directional mobile robot model [12]. The NLP method
requires an initial feasible solution to start with. Thus, different initial feasible solutions are generated by a GA method in this project. Owning to the same configuration of wheel’s distribution as Wong et al., the dynamic equations of the robot system is easily to be derived. However, as mentioned above, the solution to the dynamic equations is hard to find due to nature of the nonlinear and coupled relationship. Fortunately, the results can be presented in the form of nonlinear control algorithm with some experimental data by Wang et al [13]. Through nonlinear transformation of the initial dynamic model, the synthesized control system had begun to take shape.

In order to solve the numerical solution, it is necessary to assume the equal time interval and the fixed acceleration in the discrete domain. This assumption is only referenced for the special circumstances, the actual operation of the system is not suitable. And in the process of solution, the balance between the number of control steps and the computation should be concerned, as well as the contradiction of sampling interval and the discrete precision. Unlike the normal configuration sets of global and local different objectives[14], which needs two Lyapunov functions to derive the control law with hybrid feedback control strategy, the nonlinear programming method does not require the feedback error in control circuit, it automatically eliminates the steady-state and instantaneous error within one cycle, the error does not affect the forward cycle to the next cycle, while the hardware circuit of the system is much more complex. Considering the effect of performance, this method has the advantages on fast response, distortion reduction and interference suppression and it will be the first option for system optimization in the future.

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