PRECISE TRANSHIPPMENT CONTROL OF AN AUTOMATED MAGNETIC-GUIDED VEHICLE USING OPTICS POSITIONING

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Abstract- A parking position detection and control system is developed for precise transshipment of palletized materials between an automated guided vehicle (AGV) and a load transfer station. In order to align the roller conveyer of the AGV with that of the station, it is necessary for the AGV to detect the longitudinal, lateral and orientation deviations of its body with respect to the station. A pair of magnetic sensors is used to measure the lateral and orientation deviations of the AGV relative to a magnetic tape used as the guide-path. Fuzzy control is proposed to eliminate two deviations for path tracking that keeps the AGV on its path. A set of optics emitters and receivers is arranged on some specific points in the AGV and the station respectively to determine the longitudinal position for material transshipment, and to coordinate the transmission operation of two equipments. The experiment for the palletized materials transshipment shows that positioning control of our AGV parking system can achieve the accuracy, repeatability and reliability needed in industrial applications.

Index terms*:* Automated guided vehicle, magnetic guidance, optics positioning, parking control, cooperative transshipment.

I. INTRODUCTION

Automated material handling systems are used widely to transport products in warehouses, or distribute subparts between different assembly stations in a production line. For instance, Belt conveyor is an economical way to move most any type of product and can be used in horizontal, incline and grasping operations. Roller conveyor is popular to transport general packing or solid products in horizontal applications. These equipments are usually installed on the ground or in the mid air fixedly. Their transmission rails have to occupy some workspaces permanently and exclusively, which prevents other automated equipments or manned vehicles from traveling, and these physically-fixed paths are not convenient to change or rearrange.

Automated guided vehicle (AGV) is a driverless computer-controlled vehicle traveling along the specified paths for materials transportation. Their guidance infrastructure is not an obstacle for the movement of other equipments and their traveling route can be changed more easily than rails. So AGVs are suitable for applications where space is at a premium and flexibility is critical, which permits alternative routes that can be used to compensate machine failures or product changes [1, 2]. Besides, these vehicles also provide labor saving, overall cost reduction and safety.

Navigation and guidance is one basic function for developing an AGV, which allows the vehicle to follow a specified path. Typically, paths are specified physically by using electric wires buried in the concrete floor. Alternating currents transmitting on wires are used as inductive signals for AGV guidance, which can be detected by an on-board antenna and then followed by the AGV. However, the floor modification for burying the wires implies stopping the whole system and bringing economical costs.

The new wireless guidance systems, such as a laser scanner based navigation system, allow AGVs to operate without physical guide-paths [1], named free-ranging AGVs [2]. The position of vehicle can be estimated based on the triangular computation of returning lasers reflected from more than three fixed reflectors located in the workplace. However, the reflector visibility in workspace (e.g. the laser lights may be obstructed by a traveling crane) and the processing rate of scanning data may both influence its robustness and real-time performance in industrial settings [3]. Besides, equipment expense is also an obstacle to extensively using AGVs in cost-sensitive industries. Therefore, the original idea of embedded wires, termed the fixed-path guidance, is still widely used by other techniques, e.g., magnetic, reflective or visible tapes on the surface of the floor. Visually recognizing guide-paths can help the vehicle acquire rich guiding information, which is useful for increasing its intelligence [4, 5]. However, the complexity and reliability of the vision guidance system limit its applications in industry.

A magnetic sensor has simpler structure and lower price [6]. A magnetic tape deposited on the road in the middle of the lane generates a magnetic field, and the lateral position of the vehicle on the lane is detected by on-board magnetic sensors [7, 8]. The magnetic guidance also uses the original idea of embedded wires in the floor, but it is more convenient to paste magnetic tapes on the floor than to cut the floor for embedding wires, which can reduce the non-productive period and improve the flexibility of path layout. Therefore, this guidance approach is regarded as a compromise between device expense and system flexibility, especially suitable for developing cost-sensitive AGVs (perhaps called Automated Guided Cart, AGC) still with the grade of accuracy, repeatability and reliability required by industrial applications.

For the fixed-path guidance, path tracking techniques [9-13] are used widely to preserve the visibility of landmarks (magnetic or visible tapes on the floor) for AGVs, which can make the vehicles travel along the guide paths and avoid losing the landmarks. A kinematics equation of an AGV is combined with a first-order dynamic model of a motor for the optimal control of path tracking in [9]. However, the difference of the dynamic of a motor and the dynamic of a driving system brings the complexity and uncertainty to the control system. Usually, the adaptive control algorithm is expected to improve the robustness of the control system [11]. Fuzzy logic technique is also used to design an intelligent and stable controller for steering and speed control of an AGV. Another attempt is to present an integrated motion control model that can match the capability of the path tracking technique to correct pose errors of the AGV with that of the servo control technique to eliminate velocity errors of motors [13].

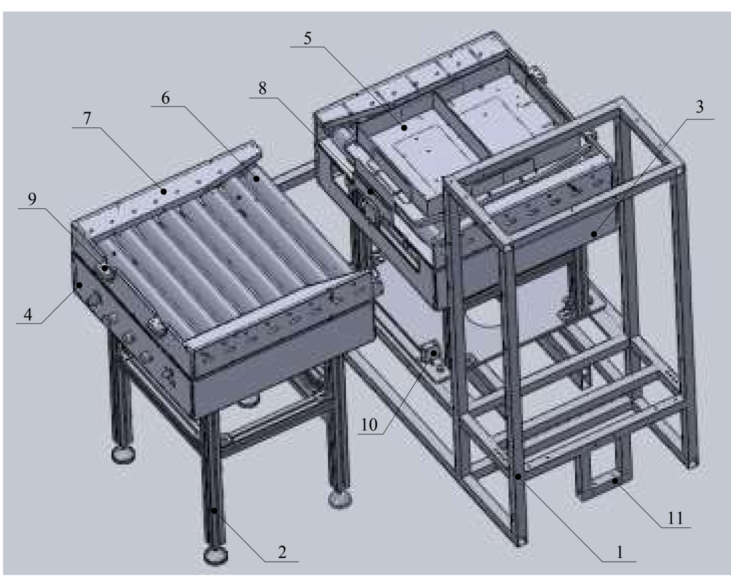
Load transfer is another important issue for AGVs to pick up and deliver materials in cooperation with other equipments in order to achieve the pervasive automation of materials transportation, although it is often neglected in many researches [14]. Robotic grippers are widely used for the picking and placing operation [15, 16], but it is not suitable for the AGV due to its low payload capacity. According to the means of load transfer, AGVs can be classified as towing AGV, unit load AGV [17], pallet truck AGV, and fork truck AGV [18]. Towing AGV was the first type introduced and is still a very popular type today. It can tow a single trailer or multiple ones by using hooks to provide traction. It has a simple structure and a capability of several times more materials than a conventional unit load AGV. However, it has difficulty to control the trailer's position accurately and has a larger turning radius. Unit load AGV is equipped with decks, which permits unit load transportation and often automatic load transfer. The decks can either be lift and lower type, powered or non-powered roller, chain or belt decks or custom decks with multiple compartments. Pallet truck AGV is designed to transport palletized loads to and from the floor level, and it can eliminate the need for fixed load stands. Fork truck AGV is ideal for applications where automatic load pickup or delivery is needed from the floor or various height elevations. It has counterbalanced or straddled leg configurations depending on application requirements.

Docking enables accurate localization without external intervention in the process of load transfer, which is a major facilitator in attaining increased autonomy [19]. A low-cost and high-precision docking system is developed in [20], in which a vertical light stripe laser beam is used to lock the direction of a robot into the docking station, and infrared sensors are used to measure the distance between the robot and the station to pull the robot into its destination. A docking method based on the self-localization of the robot and the infrared detectors of the docking station is proposed for recharging operations in [21]. A magnetic-based guidance and vision-based docking system of the AGV is presented in [22]. The vehicle detects the position of the artificial landmark on the crane from the video stream by using a CCD camera and controls its velocity to align itself with the crane. Additionally, radio frequency identification (RFID) is regarded as a promising distance estimating and locating technique that may be useful for guidance and docking of mobile robots [23-24]. It can contain a large amount of data coded information compared to magnetic and visual signs.

This paper presents a low-cost, accurate and reliable guidance and docking control system for a cost-sensitive unit load AGV with roller mechanism to implement precise parking and automatic transshipment, by combining the high accuracy and setting convenience of magnetic guidance and optics positioning with the high information capacity of RFID tags. The configuration of an AGV's transshipment system is described in section II, and how the position and orientation of the AGV with respect to a station influence load transfer is analyzed. A pair of magnetic guiding sensors is used to measure the lateral and orientation deviations of the AGV and fuzzy control is proposed for path tracking in section III. A set of optics sensors and a RFID reader are utilized for load transfer control in section IV, which identify the load stand, determine the longitudinal position and handle the transfer operation as well as the safety protection. Section V presents the transshipment experiment of palletized materials between the AGV and the load stand, and the results show the accuracy, repeatability and reliability of our system are sufficient for industrial applications. Finally, a brief conclusion is given in section VI.

II. TRANSSHIPMENT ACCURACY ANALYSIS

A load stand is the fixed port where the material pallet is transferred from the AGV to the load transfer station and back. In order to automatically transport palletized materials between a unit load AGV and the load stand, powered rollers are used to develop the decks of them, as shown in Figure 1. The mechanism of both decks consists of frame, sprocket wheels, chains, guiding railways (7) and rollers (6). A locking mechanism (8) is additionally included in the deck (3) of the AGV. A stepping motor rotates the sprocket wheel of the middle roller, and then it actuates other rollers by using sprocket wheels and chains. Two sets of optics sensors are arranged at the high and low (10) level of both decks, one for longitudinal positioning, and the other for optics communication. Two travel switches are set at the end of guiding railway of both decks, judging whether the pallet moves to the designated position. A RFID reader is mounted on the bottom bracket of the AGV frame.



1 AGV frame, 2 load stand, 3 the deck of the AGV, 4 the deck of the load stand, 5 pallet, 6 roller, 7 guiding railway, 8 locking mechanism, 9 travel switch, 10 optics sensor, 11 mounting frame for RFID reader

Figure 1. AGV system configuration

AGV's movement near the load stand is controlled differently to its movement on other ordinary guide paths since a high accuracy of the vehicle pose is needed. As shown in Figure 2, a magnetic sensor in the front of the AGV detects the signal intensity of the magnetic tape on the floor, and then the lateral position deviation (the lateral distance from the center of an AGV to the middle of a path) and orientation deviation (the angle between the lateral center lines of an AGV and a path) can be estimated. Path tracking technique is used to eliminate two deviations by adjusting the velocities of two driving wheels, so the vehicle can be controlled to align itself to the middle of magnetic tapes. The error tolerance limit of path tracking is that the deviations do not exceed the detectable range of a magnetic sensor, which implies the AGV still keep itself on guide paths.

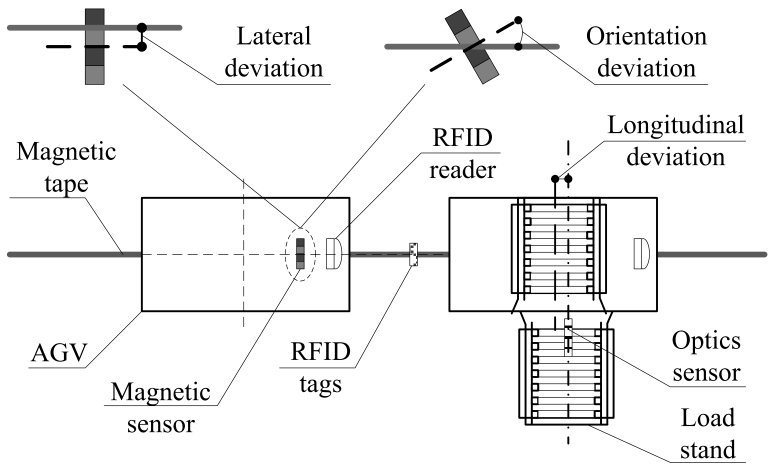


Figure 2. AGV docking process

However, much higher pose accuracy is necessary for load transfer between an AGV and a load stand in order to convey a pallet from one deck to the other in an unhindered way. Besides two deviations mentioned above, the longitudinal position deviation (the longitudinal distance from the center of an AGV to that of a load stand) also has to be considered for this situation. The error tolerance limit of load transfer is that the movement of the pallet does not interfere with the guiding railway, which is much smaller than the limit of path tracking since the clearance (usually at the unit of millimeter) of the pallet and the railway is obviously smaller than the detectable range (usually at the unit of centimeter) of the magnetic sensor. Therefore, a different control approach is adopted for docking the AGV with the load stand.

As shown in Figure 2, a RFID tag that identifies a workstation with some specific operations is placed on the magnetic tape before the load stand. When the RFID reader detects the tag, the AGV knows there is a load transfer station in front, and begins to wait for the positioning signal from the optics emitter on the load stand. When the optics receiver at the low level of the AGV captures the light signal, the vehicle reduces its speed to zero gradually at a proper acceleration.

Once the AGV stops, the distance of the longitudinal center lines of the vehicle and the station is the longitudinal deviation of AGV parking. If the load stand is placed on an accurate position and orientation relative to the magnetic tape beforehand, the lateral and orientation deviations of the vehicle and the station (termed as AGV parking deviations) are equivalent to the deviations of the vehicle and the tape (termed as AGV guidance deviations). However, the latter can be measured conveniently by using on-board magnetic sensors.

After the AGV accomplishes the docking process, three deviations of AGV parking influence the operations of load transfer to different extent. As shown in Figure 3, the guiding railway of a deck has a V-shaped entrance that can help to rectify the pose errors of the pallet and facilitate its movement into this deck. When both sides of the pallet do not exceed the left and right limits of the V-shaped entrance, the pallet can move from one deck into the other one successfully, which is the error tolerance limit of load transfer.

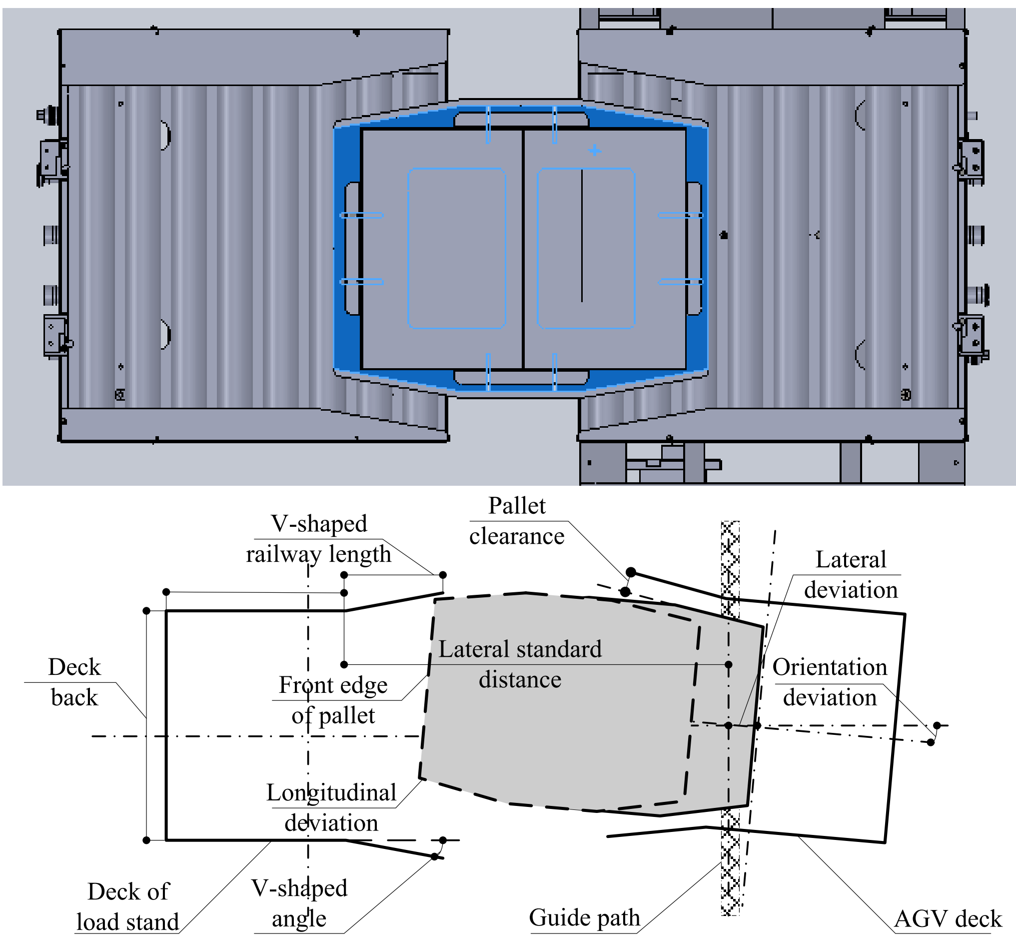


Figure 3. Transshipment error analysis

When the load stand is placed besides the magnetic tape, the lateral distance from the center of the load stand to the middle of the tape is preset as a standard distance D_L. Structure parameters of decks are designed as follows, the length of the V-shaped railway L_V, the V-shaped angle of the railway θ_V, and the clearance of the pallet and the railway L_C. AGV parking deviations are detected by sensors as follows, the lateral deviation e_d, the longitudinal deviation e_a, and the orientation deviation e_θ. Suppose all deviations are on the most adverse conditions at the same time, and the error tolerance limit of load transfer can be formulized as

$$(e_d + D_L)\tan e_\theta + e_a \le L_C + L_V \sin\theta_V \qquad (1)$$

Usually, e_d is smaller than D_L at several orders of magnitude, so it has a small influence on the limit condition, which can be ignored at most time. Since the change rate of the tangent function has a rapid upstroke, e_θ is a severe hindrance to the accuracy of load transfer. L_C and L_V are relatively small with respect to D_L, and e_a also has a direct influence on the transfer accuracy.

Besides AGV parking deviations, another interference factor for load transfer is the conformance of friction-drive forces provided by powered rollers to the pallet. If the resultant force of friction is not parallel with the railway, two endpoints of the front edge of the pallet can not achieve in contact with the deck back at the same time, as shown in Figure 3. This pose error of the pallet on the deck may influence the next operation of load transfer, and the error may be accumulated gradually to a fairly large value that exceeds the error tolerance limit of load transfer eventually. It is obvious that this error should be eliminated in each time of the material handling operation. Two travel switches are mounted on the deck back, which guarantees a full-surface contact of the front edge of the pallet to the deck back, so the pallet can arrive at an accurate pose on the deck after each operation.

In order to deposit and retrieve the pallet between two decks with a highly repeatable accuracy, two control techniques are used to correct these four errors analyzed above. One is the path tracking technique that reduces the lateral and orientation deviations of the AGV relative to the magnetic tape (equivalent to the deviations of the AGV and the load stand, which is guaranteed by the design stage of the transshipment system). The other is the load transfer technique that eliminates the longitudinal deviation of the AGV by using the optics positioning and the pose error of the pallet on the deck by using the contact feedback of travel switches, and controls the operating process by using the optics communication.

III. PATH TRACKING CONTROL

Magnetic tapes are used as the guiding lines for the fixed-path guidance of our AGV, as shown in Figure 4. Several measuring points that can detect the magnetic signals of magnetic tapes are evenly distributed on a magnetic sensor. When the measuring points that find the guiding signals are not in the middle of the sensor, a lateral deviation occurs between the AGV and its guiding line. The number and interval of points determines the detecting range of guiding sensors, and also the maximum lateral deviation before an AGV loses its guiding lines. Usually, a low-cost sensor has a few measuring points and a small range, e.g., our sensor only has 6 measuring points, and the interval between two points is 2cm.

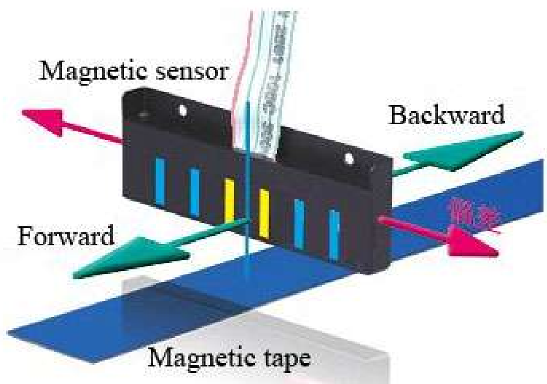


Figure 4. Magnetic guidance of an AGV

It is obvious that only one magnetic sensor can not measure the orientation deviation. Therefore, two sensors are mounted in a parallel way with a longitudinal interval W_S on the chassis of the AGV. Figure 5 shows two magnetic sensors respectively measure their lateral deviations from the tape, denoted as e_{d1} for the forward sensor and e_{d2} for the backward one. Since the middle point of the sensor interval overlaps with the center of the AGV (designated by the middle point of the common axis of two driving wheels), the lateral deviation of the AGV can be estimated by using two observed values of sensors, shown

$$e_d = \frac{e_{d1} + e_{d2}}{2} \tag{2}$$

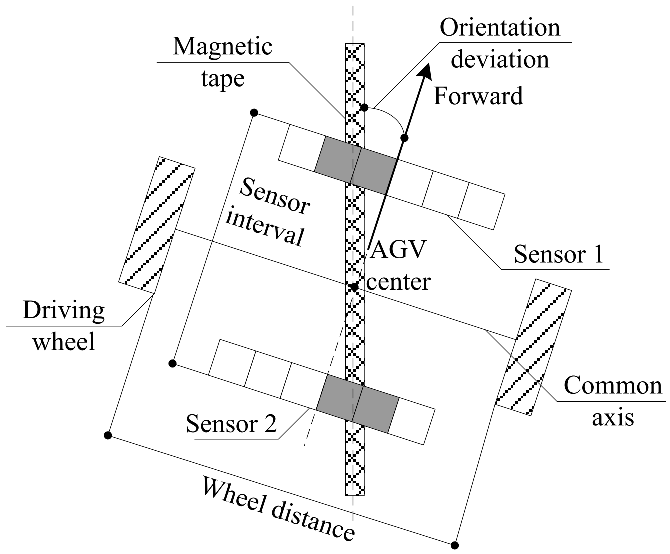


Figure 5. Measurement of the orientation deviation

The orientation deviation of the AGV can also be expressed by

$$e_\theta = \tan^{-1}\frac{e_{d1} - e_{d2}}{W_S} \tag{3}$$

Figure 6 shows the kinematics sketch of a differential driving AGV. The distance of two driving wheels is W, the linear velocity of the left and right driving wheel is v_l and v_r respectively, the linear velocity of the AGV's center is v, and the angular velocity is ω when AGV moves along arc trajectories. According to the kinematics principle of rigid body, we can get

$$v = \frac{v_l + v_r}{2} \tag{4}$$

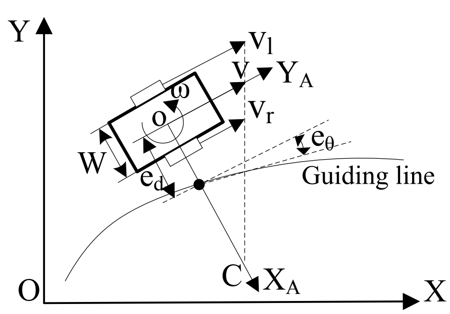


Figure 6. AGV movement sketch

When two deviations occur, the speed difference output Δv between two driving wheels is regulated to make the AGV move along arc trajectories and approach guiding lines, resulting in the elimination of the lateral deviation e_d and orientation deviation e_θ. In order to keep the linear velocity of the AGV's center unvaried, the linear velocities of driving wheels become

$$\begin{aligned} v_l &= v + \Delta v \\ v_r &= v - \Delta v \end{aligned} \tag{5}$$

The angular velocity of the AGV is

$$\omega = \frac{(v_l - v_r)}{W} = \frac{2\Delta v}{W} \tag{6}$$

As shown in Figure 6, when the motion state k is turned to the motion state k+1 over the sampling interval T_s, the angle that the AGV rotates around the instantaneous velocity center A is ωT_s. The linear kinematics equation [13] on the condition of the small orientation deviation is

$$\begin{cases} e_\theta(k+1) = e_\theta(k) + \dfrac{2T_s}{W}\Delta v(k) \\ e_d(k+1) = e_d(k) - v e_\theta(k) T_s - v\dfrac{T_s^2}{W}\Delta v(k) \end{cases} \tag{7}$$

Equation (7) shows it is a control system of double inputs and single-output. The fuzzy control technique is used to eliminate two deviations. The detecting range of magnetic sensors for the lateral deviation is from -5cm to 5cm. The interval W_S of two sensors is preset as 40cm. The maximum angle detectable by using two sensors is $\pm 15^\circ$ according to Equation (3). The fuzzy domains of the lateral deviation and orientation deviation are designed as {-3, -2, -1, 0, 1, 2, 3}, and the fuzzy subsets are designated as NB, NM, NS, ZO, PS, PM, PB. The trimf membership function is used to convert the exact measured values to the fuzzy values for two deviations, as shown in Figure 7 and 8.

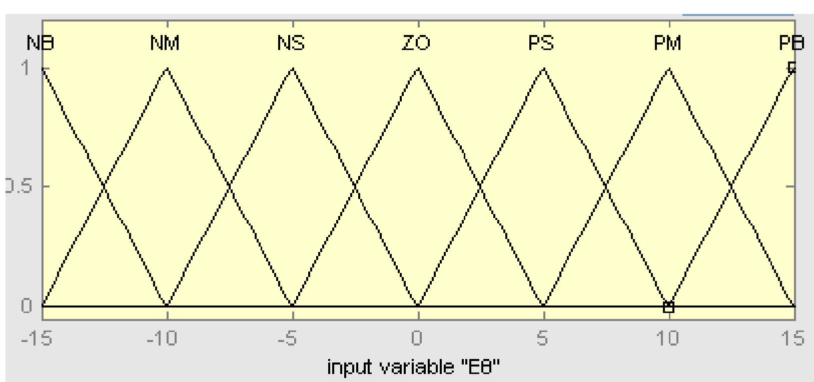


Figure 7. Membership function of the orientation deviation

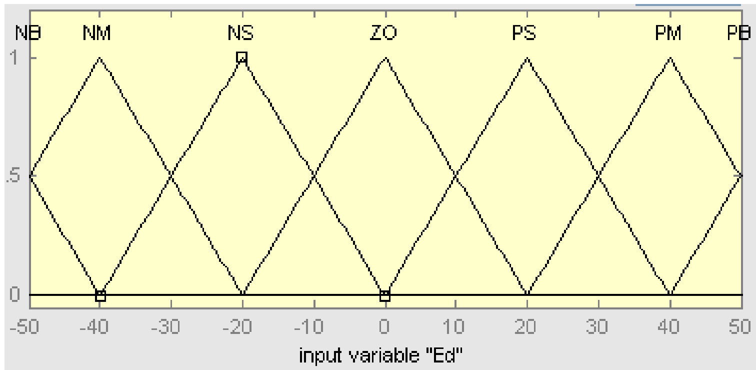


Figure 8. Membership function of the lateral deviation

The experiences of human drivers are used as a technical reference to build a fuzzy rule base, as shown in Table 1. For human drivers, the control output may be not optimal in quantity to correct deviations, but must be reasonable in steering direction. When e_d and e_θ are both large in the same polarity (positive or negative), the control output Δv should become large in the opposite polarity to avoid missing the guide path in the detecting range of the AGV. When e_d and e_θ are in the opposite polarity, it is not necessary to increase the control output greatly because there is enough time to correct deviations before the AGV is lost. The digital control system produces the output in each sampling period, and the system dynamics in each period is simplified. The fuzzy rule base can also be illustrated by using a spatial surface, as shown in Figure 9.

All control outputs corresponding to each input state are obtained by fuzzy reasoning, and then translated to the exact values by using the centroid method, as shown

$$Z = \sum_{i=1}^{n} \frac{\mu_c(z_i) \times z_i}{\sum_{i=1}^{n} \mu_c(z_i)} \tag{8}$$

All exact outputs of fuzzy control are collected as a control table stored in the memory of an on-board controller and available for the online searching. Based on the kinematics model (7), the process that an AGV follows a curvilinear path is simulated digitally in the software MATLAB. Two initial deviations are set as zero, the sampling period is fixed at 0.2 ms, and the AGV's speed is at 1 m/s. The simulation results are shown in Figure 10. The desired path includes a segment of straight line and curve. The AGV starts to travel at a zero-error initial state, so it is easy to keep the actual trajectory in accordance with the desired linear path. However, when it enters the curvilinear path, two deviations increase rapidly, and the fuzzy controller begins to eliminate them effectively. Only one overshoot occurs in the process that the AGV approaches the desired path, and after that the AGV can keep itself on the path.

Table 1: Fuzzy rule base

e_θ \ e_d	**NB**	**NM**	**NS**	**ZO**	**PS**	**PM**	**PB**
NB	PB	PB	PB	PB	ZO	ZO	ZO
NM	PB	PM	PM	PM	ZO	ZO	ZO
NS	PB	PM	PS	PS	ZO	ZO	ZO
ZO	PB	PM	PS	ZO	NS	NM	NB
PS	ZO	ZO	ZO	NS	NS	NM	NB
PM	ZO	ZO	ZO	NM	NM	NM	NB
PB	ZO	ZO	ZO	NB	NB	NB	NB

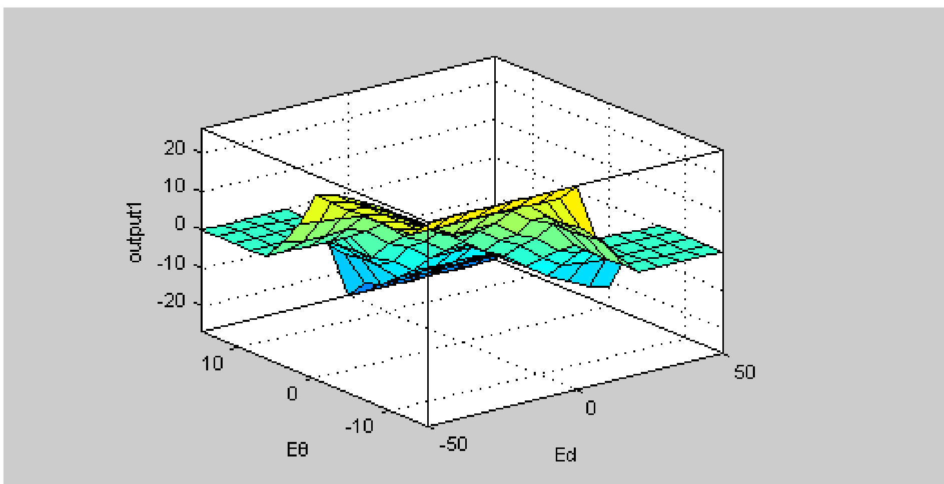


Figure 9. Geometric representation of the fuzzy rule

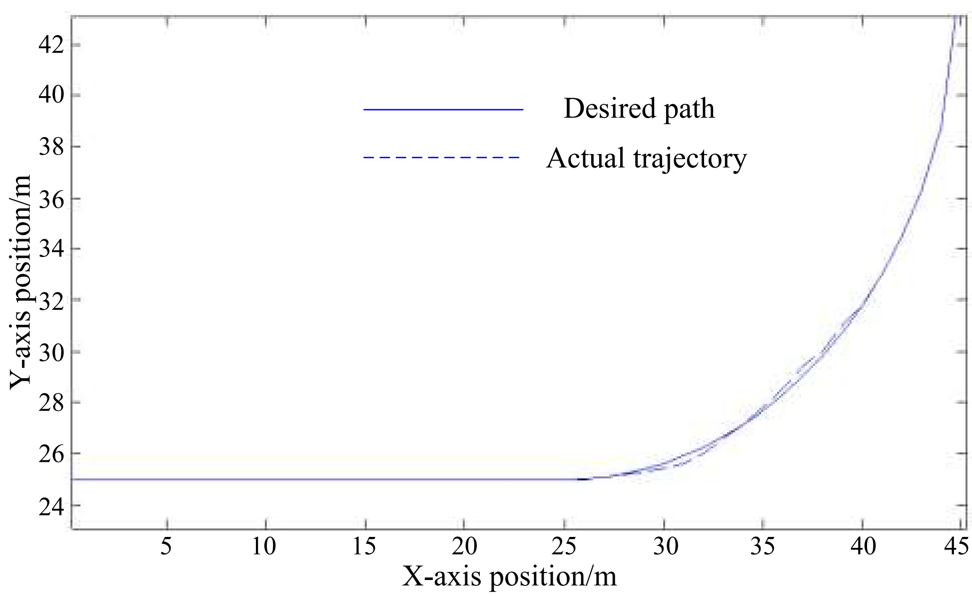


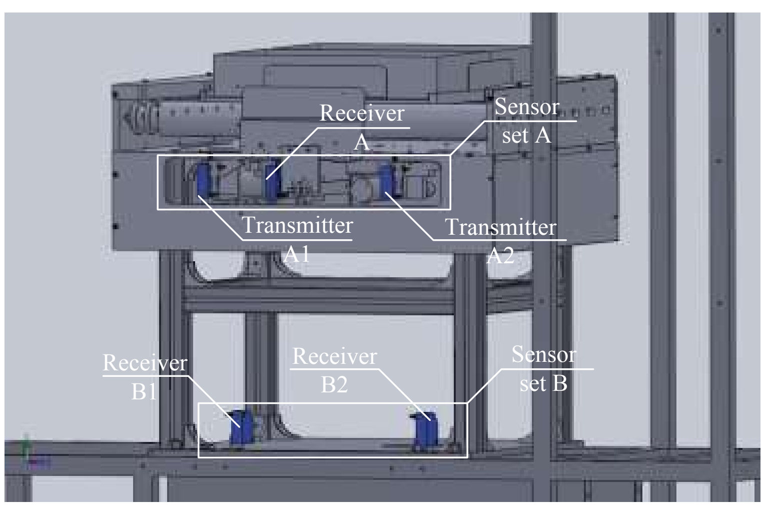
Figure 10. Simulation of path tracking

IV. LOAD TRANSFER CONTROL

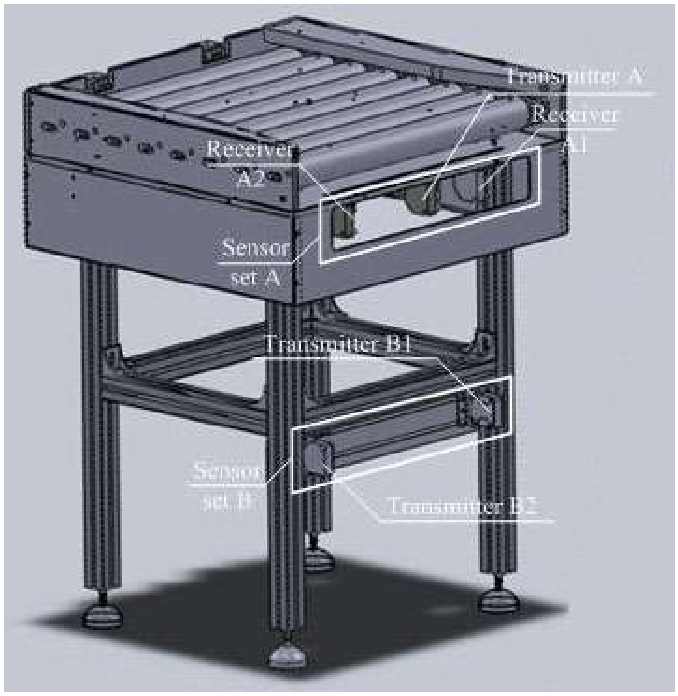
This section deals with two main issues in the process of load transfer between the AGV and the load stand. One is to guarantee the accurate longitudinal position of the AGV when it stops besides the load stand. The other is to control the operating process of load transfer as well as to correct the pose error of the pallet when it is driven by powered rollers.

a. Longitudinal positioning

Although the RFID technique is regarded as a promising locating approach [23-24], its existing low-cost product solutions (e.g. passive tags and their readers) are still subject to percept distance and locating precision. Therefore, the passive RFID tags are only used here to store the station information and to indicate a rough location for AGV parking. When the RFID reader detects the station tag, the AGV switches to the docking control state. Two optics receivers are set at the low level of the AGV for longitudinal positioning, shown as SENSOR SET B in Figure 11(a). The corresponding optics transmitters are mounted on the load stand, shown as SENSOR SET B in Figure 11(b). SENSOR SET B of the load stand consists of two optics transmitters that provide the light signals for the longitudinal position of the AGV. When the AGV gets close to the load stand, receiver B2 captures the signal from transmitter B1 ahead of receiver B1. Then the AGV begins to reduce its speed v to zero at an acceleration α .



(a) Optics sensors on the AGV



(b) Optics sensors on the load stand

Figure 11. Placement of optics sensors

The theoretical distance of AGV parking can be estimated

$$L_P = \int_{t=0}^{T} (v + \alpha t)\mathrm{d}t \tag{9}$$

Where T is the time when the AGV's speed is decreased to zero from the initial value v.

The distance of optics receivers B1 and B2 on the AGV is preset according to the theoretical value L_P. That of optics transmitters B1 and B2 on the load stand should be adjusted on the debugging stage in order to compensate the possible errors of AGV parking. This distance of two transmitters is regulated slightly larger than that of two receivers, and the increased distance is limited to the tolerable longitudinal error e_a calculated by Equation (1), as shown in Figure 12.

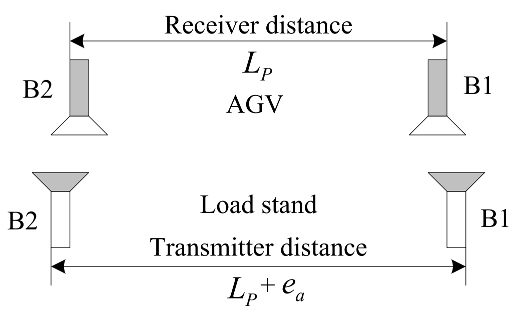


Figure 12. Distance regulation of optics sensors

The AGV's speed is reduced to zero immediately by using a compelling solenoid brake when receiver B2 gets the signal from transmitter B2 or when receiver B1 gets the signal from transmitter B1. As shown in Figure 12, optics receivers B1 and B2 are located on the middle area between transmitters B1 and B2 strictly, which can ensure that the longitudinal deviation e_a does not exceed the error tolerance limit of AGV parking reliably. Therefore, the deck of the AGV can be docked accurately with the deck of the load stand for the next operation of pallet transfer.

b. Transfer operation

Load transfer needs the movement coordination of powered rollers of both the AGV's deck and the deck of load stand as well as the safety operation for emergency. Three pairs of optics sensors are mounted at the high level of the AGV and the load stand for optics communication, shown as SENSOR SET A in Figure 11(a) and Figure 11(b). When the AGV is docked with the load stand, optics transmitter A1, A2 and A are located directly opposite to receivers A1, A2 and A. Figure 1 shows that there are two travel switches at the end of guiding railways of both decks in order to check whether the front edge of the pallet contacts the deck back in the whole length.
Another two travel switches are used in the locking device on the AGV's deck, which prevents the pallet from sliding in the guiding railway when the AGV changes its speed at a large acceleration or turns at a small radius. A crank rocker mechanism is designed for the function of locking and unlocking, and two travel switches are mounted on the collinear positions of the crank and the conrod, as shown in Figure 13.

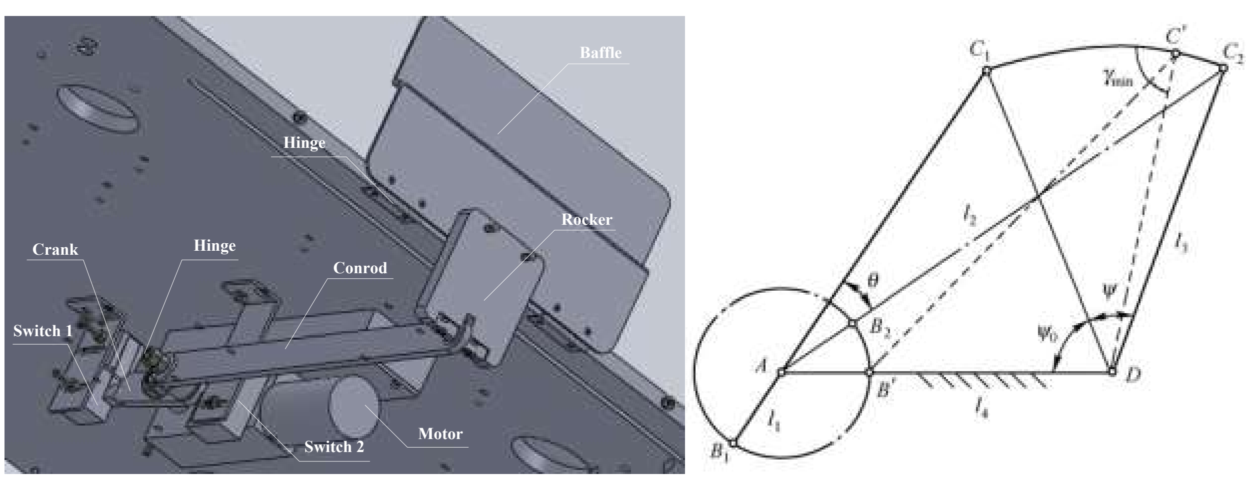


Figure. 13 Locking device with its travel switches

When the crank rotates to the position AB_1 and the conrod to the position B_1C_1, the rocker swings to the left limit position C_1D, which is the locking state for the pallet. Travel switch 1 is mounted on point B_1 that can be pressed down when the crank rotates to this position. When the crank rotates to the position AB_2 and the conrod to the position B_2C_2, the rocker swings to the right limit position C_2D, which is the unlocking state for the pallet. Travel switch 2 is mounted on point B_2 that can be pressed down when the crank rotates to this position. A DC motor is used to actuate the crank, and to stop it on the position AB_1 and AB_2 respectively based on the signal feedbacks of two switches, in order to lock and unlock the pallet.

Figure 14 shows the process control of depositing operation that the AGV puts down the pallet to the station. After the AGV is accurately docked with the load stand, the depositing operation starts with the unlock instruction to the locking mechanism. The crank pulls the rocker to the right limit position when it contacts travel switch 2. The baffle linked with the rocker is open, and the pallet can be transferred to the deck of load stand.

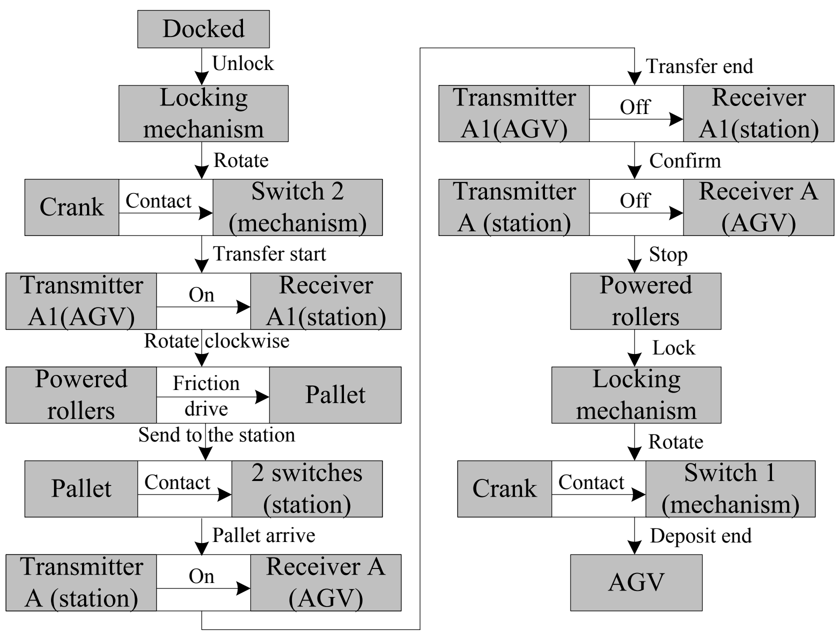


Figure 14. Process control of depositing pallet

Optics transmitter A1 of the AGV emits a light signal to receiver A1 of the load stand, and then both of them rotate clockwise their powered rollers to drive the pallet from the AGV to the load stand. When the front edge of the pallet contacts two travel switches on the deck back of the load stand reliably, the pallet arrives at an accurate pose on the deck. Then optics transmitter A of the load stand turns on the light signal to receiver A of the AGV. When the AGV gets the message of pallet arrival, it turns off transmitter A1 and receiver A1 of the load stand loses the light signal.

So the load stand knows that the AGV has accepted the arrival signal, and it turns off transmitter A to confirm the instruction of transfer stop with the AGV. Then both of them stop powered rollers, and the AGV sends the lock instruction to the locking mechanism. When the crank contacts travel switch 1, the baffle linked with the rocker is close and the pallet is grasped firmly. The whole depositing operation is completed here. The retrieving operation that the AGV picks up the pallet from the station has a similar process, also including unlock, transfer start, pallet arrival, transfer stop, and lock, etc.

V. TRANSHIPMENT EXPERIMENT

A cost-sensitive unit load AGV system is developed for the precise automatic transshipment of palletized materials, as shown in Figure 15. A closed-loop rectangle-shaped guide path is laid out on the floor by using magnetic tapes. There are four circular segments on each corner of guide path. The load stand is placed at an accurately designated spot beside a linear segment of path, two ends of which are connected with circular segments. A RFID tag is set on the floor close to the magnetic tape before the load stand, which identifies it as a load pickup workstation as well as a load delivery workstation. The transshipment experiment of palletized materials is carried out by using this prototype system on the guidance infrastructure. When the transport system runs continuously, the operations of depositing and retrieving are performed by the AGV alternately, one closed-loop travel for putting down the pallet, and the other travel for picking up it.

The path tracking technique is used to eliminate the lateral and orientation deviations when the AGV follows the magnetic tapes or aligns itself to the load stand. Two magnetic sensors are placed in a parallel way on the chassis of the AGV. Each sensor has 6 measuring points, and their scale values are -50mm, -30mm, -10mm, 10mm, 30mm and 50mm respectively from the left to the right. The longitudinal distance W_S of two sensors is 360mm. The width of magnetic tapes is 30 mm. When the AGV travels on the guide path, one or two measuring points of sensors can capture the magnetic signals of tapes. The position deviation is calculated by averaging the scale values of measuring points that find the magnetic signals. The real-time data of two sensors are saved by the on-board embedded controller of the AGV at each sampling interval (0.1s), and it transmits the data to the monitoring control software on a host computer in a wireless way. The data is recorded into a database by the control software on the online stage of the experiment, and then extracted by the analysis software for a further process on the offline stage. A section of real-time data that describes the movement process of the AGV traveling from a circular segment to a linear one is illustrated as a series of error curves in Figure 16.

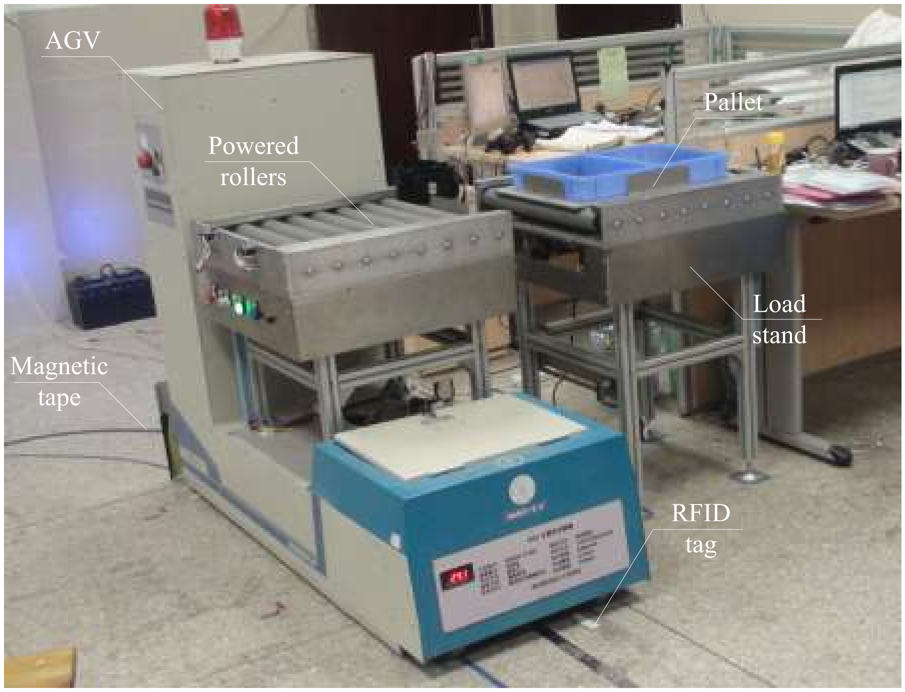


Figure 15. AGV prototype system

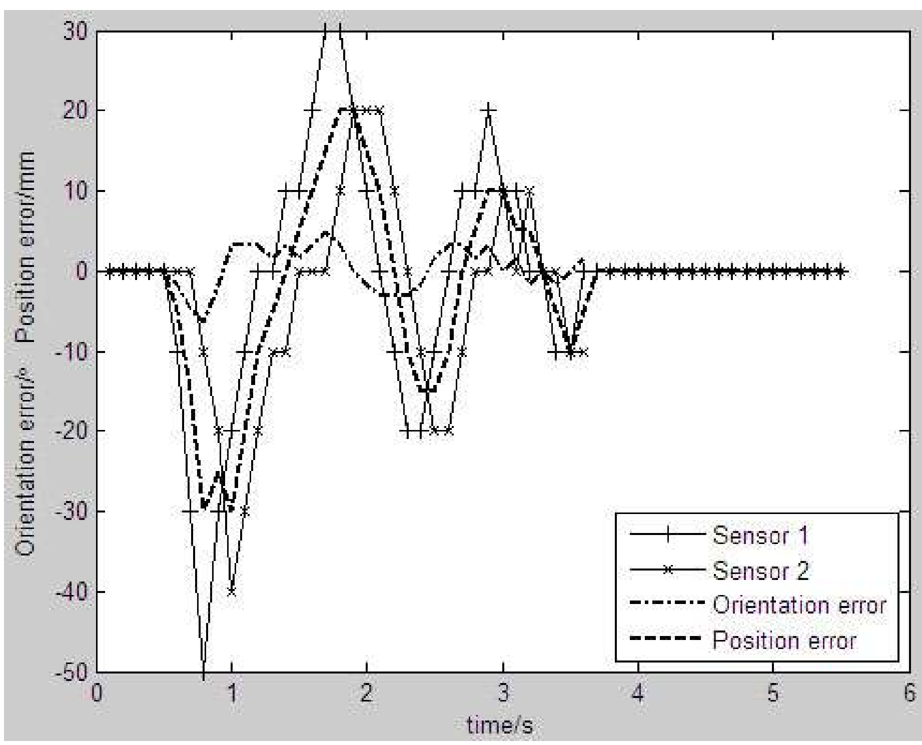


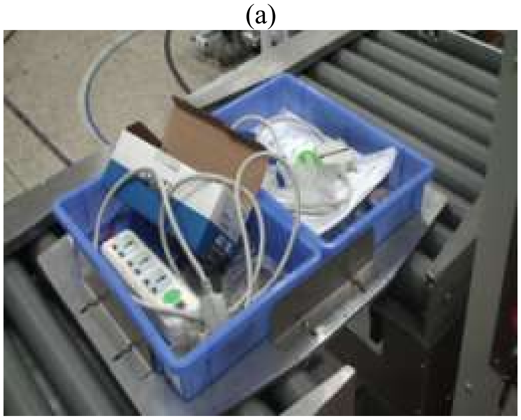
Figure 16. Error curve of path tracking

The AGV's speed is 0.4 m/s, and the radius of the circular segment is 0.5 m. In order to test the tracking ability of the fuzzy control algorithm for any circular pathway of unknown curvature, the radius of 0.5 m is not used deliberately as a prior knowledge in the control process. It implies the control algorithm does not distinguish the linear path with the circular path. Therefore, When the AGV enters the left-turning circular segment, it does not know the path curvature changes, but it finds the position deviations measured by two magnetic sensors increase dramatically in the negative direction. A large control output of speed difference is generated by the fuzzy controller to pull the AGV back to the guide path. Although there are two oscillation waves in the error curves, their amplitudes keep decreasing at a fast rate and do not exceed the detecting ranges of sensors. Only the front magnetic sensor has one position deviation up to the maximum value of -50 mm, and the rear magnetic sensor has relatively smaller deviations than it. The AGV's center is the middle point of the sensor interval, and its lateral and orientation deviations are represented as a dashed curve and dash-dotted curve in Figure 16. The AGV keeps its lateral deviation within the range of ±30 mm, and prevents its orientation deviation beyond the limit of ±10°. When the AGV moves into the linear segment again, its deviations decrease to zero and then it maintains an error-free tracking state. It can be seen that the fuzzy controller can provide the sufficient tracking accuracy on the lateral position and orientation for guiding and docking the AGV.

When the AGV reads the RFID tag of the load stand, it converts from the guidance mode into the docking mode, and it reduces the traveling speed to 0.2 m/s. When optics receiver B2 captures the positioning signal from the load stand, the AGV reduces its speed to 0 at an acceleration of 0.2 m/s^2. The theoretical distance L_p of AGV parking is 0.3 m. The structure parameters of the deck are as follows. The standard distance D_L is 800mm, the length of the V-shaped railway L_V is 250 mm, the V-shaped angle of the railway θ_V is 10°, and the clearance of the pallet and the railway L_C is 10mm. Figure 16 shows two deviations are 0 when the AGV travels on the linear segment or stops at the positioning spot. However, since the interval between two measuring points is 20mm, the possible maximum measuring errors of the lateral and orientation deviation are e_d^m=10mm and e_θ^m=3°. According to Equation (1), the maximum longitudinal deviation of AGV parking that complies with the error tolerance limit of load transfer is 12mm. The parking accuracy is reliably guaranteed by optics positioning in the experiment. Figure 17 shows the video screenshot of load transfer between the AGV and the load stand.

(a)

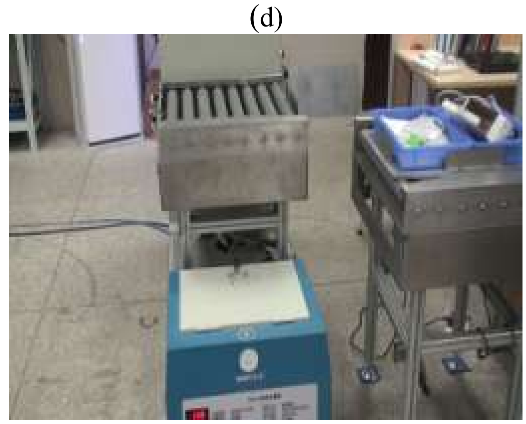
(b)



(c)

(d)

(e)



(f)

Figure 17. Load transfer process

It can be seen that the AGV is docked precisely with the load stand (Figure 17.(a)). After the locking device opens the baffle (Figure 17.(b)), the pallet is conveyed from the AGV to the load stand by frictionally driving of powered rollers (Figure 17.(c)). Due to the inconsistency of friction forces of rollers, the movement direction of the pallet does not parallel with the railway. As a result, the front edge of the pallet contacts the right travel switch of the deck back first (Figure 17.(d)). Powered rollers continue to drive the pallet until both endpoints of its front edge press down two travel switches (Figure 17.(e)). After the pallet arrives at the accurate pose on the deck, the locking device closes the baffle and the AGV departs from the load stand (Figure 17.(f)). In order to test the repeatability and reliability of the transport system, the operations of depositing and retrieving are performed hundreds of times in a continuous way. Although the longitudinal deviation of the AGV is not measured due to the finite functions of optics sensors, the positioning error of the pallet can be expressed by checking the clearance variance between the pallet and the railway. Experimental results show the clearance variance keeps within the range of ±5 mm, which can achieve the repeatable accuracy needed by automatic transport. The guidance control system of our AGV prototype is developed by using low-cost magnetic and optics sensors, but its performances still meet the demand of industrial applications.

VI. CONCLUSIONS

An accurate guidance and docking control system is developed for a cost-sensitive unit load AGV with the roller mechanism to transfer palletized materials automatically. The AGV is guided by following the magnetic tapes on the fixed path, and the load stand is recognized by using a RFID tag besides the path. The transshipment accuracy of the pallet between two decks is analyzed in the process of AGV parking as well as roller driving. The lateral, longitudinal and orientation deviations of AGV movement and the inconsistent error of roller driving influence the final pose of the pallet on the deck together. On the stage of system configuration, the load stand is placed on an accurate position and orientation relative to the magnetic tape, so AGV parking deviations are equivalent to AGV guidance deviations. A pair of magnetic guiding sensors is used to measure the lateral and orientation deviations of the AGV and fuzzy control is proposed to accomplish path tracking. The longitudinal position of the AGV is guaranteed by stopping the vehicle at a proper acceleration when its optics sensor receives the positioning signal. The operations of push and pull are coordinated between the AGV and the load stand in the way of light communication by using another set of optics sensors. Two travel switches on the deck back is used for pose control that keeps the pallet parallel with the railway of the deck after each operation. The transshipment experiment of palletized materials is carried out hundreds of times on our AGV prototype system. Experimental results show the cost-sensitive AGV system can still achieve the accuracy, repeatability and reliability needed in industrial applications.

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