



























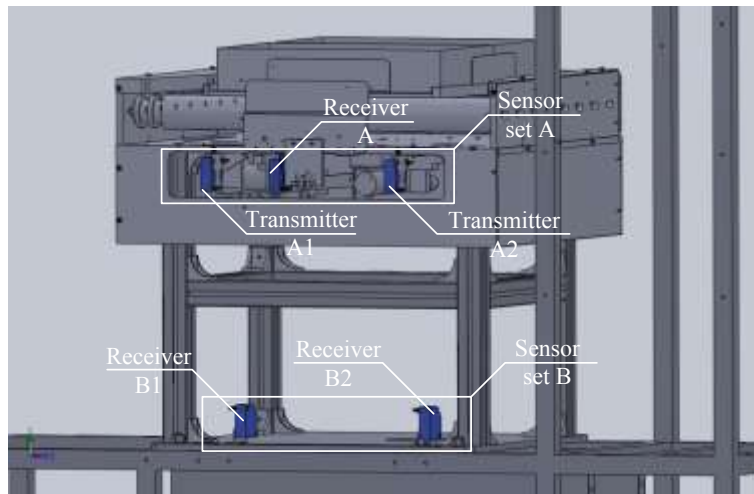


#### IV. LOAD TRANSFER CONTROL

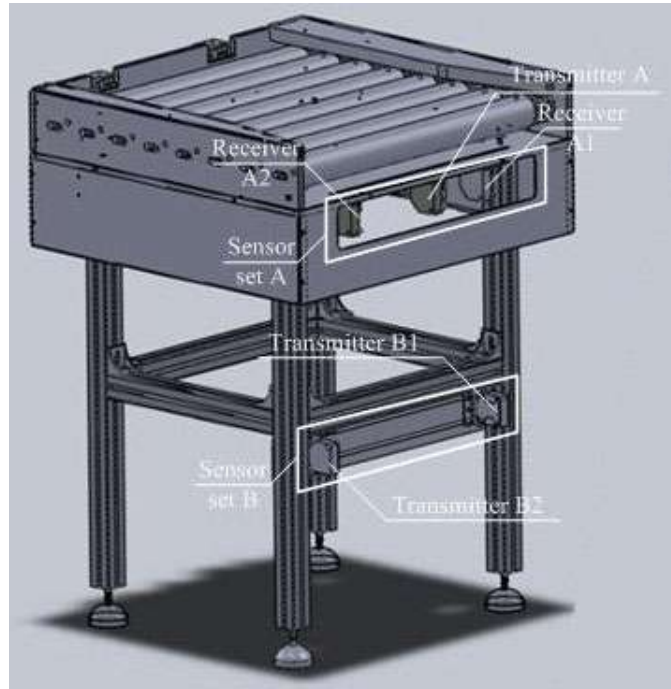
This section deals with two main issues in the process of load transfer between the AGV and the load stand. One is to guarantee the accurate longitudinal position of the AGV when it stops besides the load stand. The other is to control the operating process of load transfer as well as to correct the 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  $\alpha$ .



(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

$$L_p = \int_{t=0}^T (v + \alpha t) dt \tag{9}$$

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.

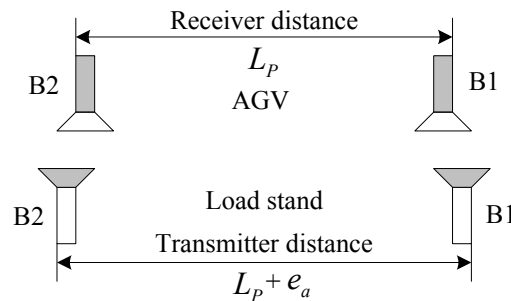


Figure 12. Distance regulation of optics sensors

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.

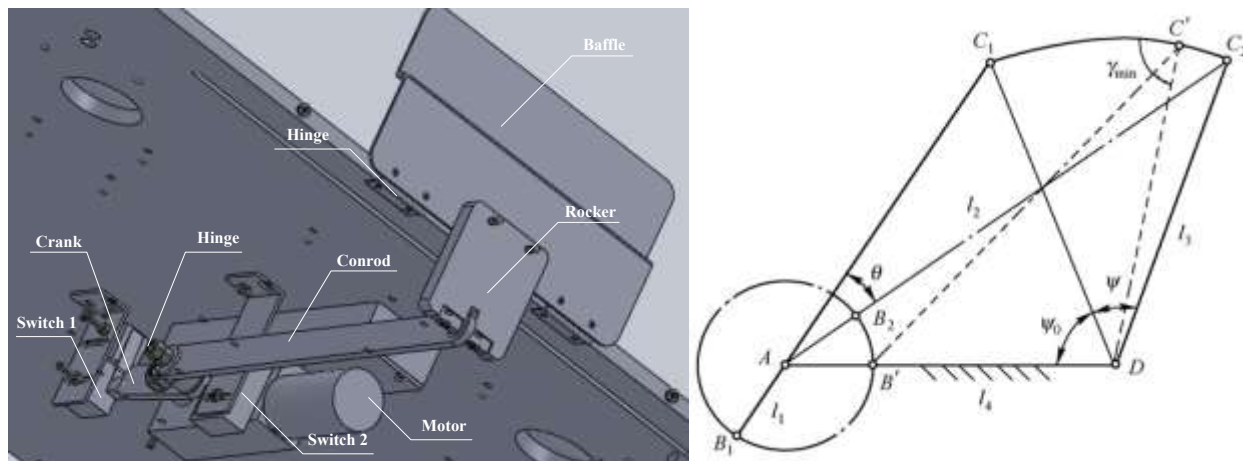


Figure. 13 Locking device with its travel switches



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.

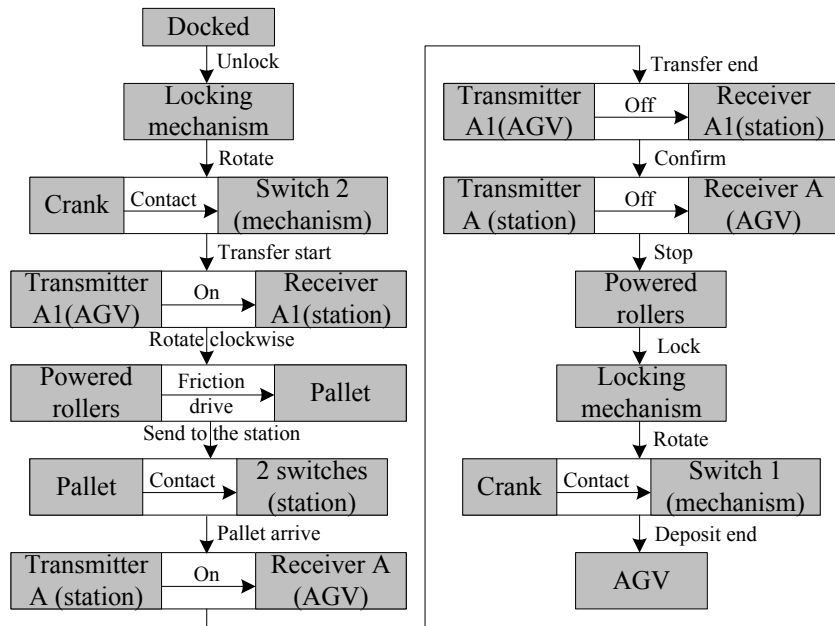


Figure 14. Process control of depositing pallet

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.

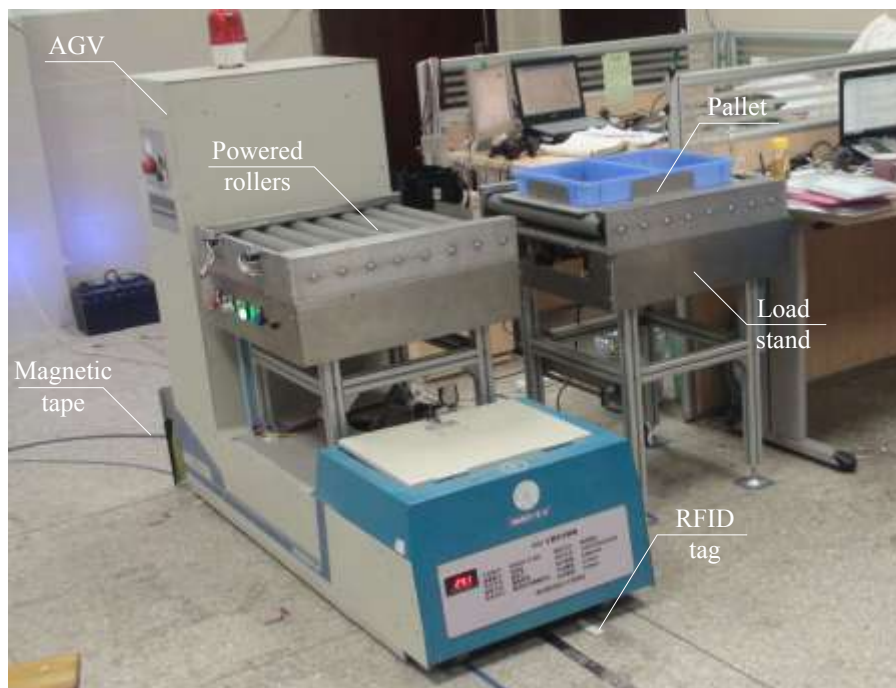


Figure 15. AGV prototype system

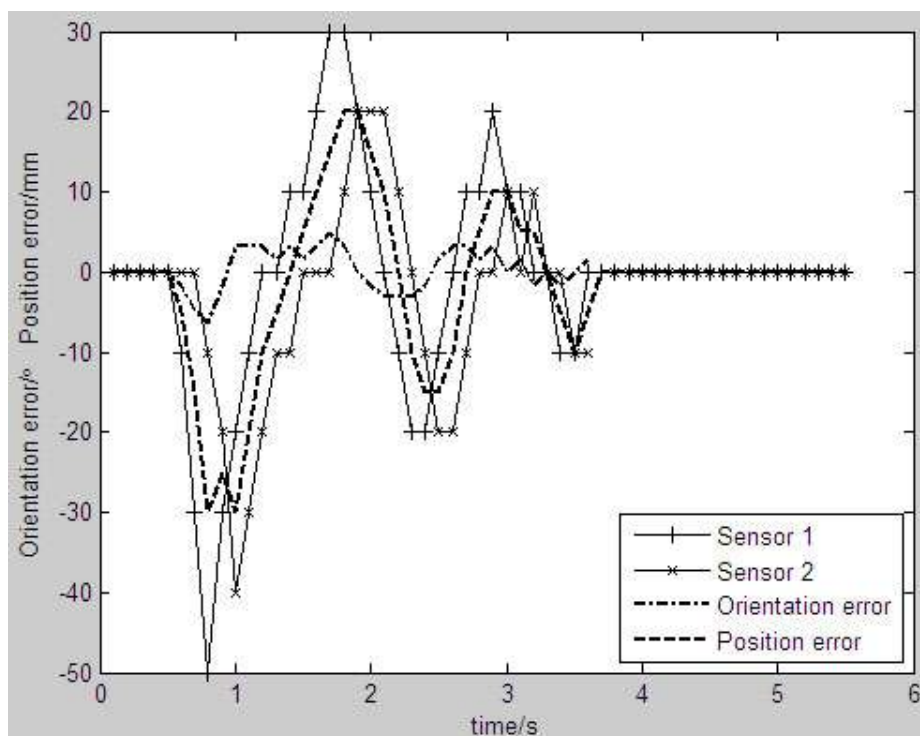


Figure 16. Error curve of path tracking

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  $\pm 30$  mm, and prevents its orientation deviation beyond the limit of  $\pm 10^\circ$ . 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  $0.2 \text{ m/s}^2$ . 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  $\theta_V$  is  $10^\circ$ , 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  $e_d^m=10\text{mm}$  and  $e_\theta^m=3^\circ$ . 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  $\pm 5$  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.

## ACKNOWLEDGMENTS

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