Mobile Robot Transportation for Multiple Labware with Hybrid Pose Correction in Life Science Laboratories

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Abstract:
In automated working environments, mobile robots can be used for different purposes such as material handling, domestic services, and objects transportation. This work presents a transportation process for multiple labware with hybrid pose correction in life science laboratories using H20 mobile robots. Multiple labware and tube racks, which contain chemical and biological components, have to be transported safely between laboratories on different floors of life science environment. Therefore, an accurate approach for labware transportation is required. The H20 robot has dual arms each consisting of 6 revolute joints with 6-DOF. The problem statement of robot positioning error in front of the workstation is presented. The navigation strategy with its related systems is presented for multi-floor mobile robot transportation environment. A Stargazer module is used as a stable and low-cost mapping and localization sensor with artificial landmarks. An error management system to overcome incorrect stargazer reading problems is presented. Different strategies of pose correction for mobile robots are described. The H20 robot is equipped with sonar sensors and Kinect V2 to be used for labware manipulation and position correction. The Kinect sensor V2 with SURF algorithm (Speeded-Up Robust Features) is used to recognize and localize the target. The communication procedure between the transportation platforms is done using client-server models.

Keywords: *robot position correction, multiple labware transportation, mobile robot localization, motor encoder, localization error handler, Kinect V2, grasping and placing operation, multi-floor*

1. Introduction

Mobile robots are widely used to perform different tasks in automation fields such as product transportation [1], domestic services [2], teleoperation [3], or material handling [4]. In this work, a labware transportation system using mobile robots (H20 robot, Dr. Robot, Canada) in a life science environment is presented. H20 robot is a wireless networked autonomous humanoid mobile robot. It has a PC tablet, dual arms, and an indoor GPS navigation system (see Fig. 1). The labware, which is shown in Fig. 2, contains chemical and/or biological components. Dealing with such objects requires an accurate and secure manipulation with transportation because any kind of spilling has to be avoided. Some technical achievements have been developed at the Center for Life Science Automation (Celisca, University of Rostock) to improve the H20 transportation system [5], [6]. Different automation islands in different laboratories and floors can be connected using stationary and mobile robots. This connection leads to increased productivity and saves human resources by ensuring a 24/7 operation and by reducing the routine work for the employees. This requires several prerequisites like robot navigation control, object recognition with position estimation, and arm control. The navigation system includes the mapping, robot localization and path planning. Related to object manipulation, the robotic arm has to be guided to the target. The target pose can be acquired visually using a suitable sensor with a proper recognition algorithm. Then, the kinematic model is used to calculate the required joints' angles that guide the arm end-effector to the desired object accurately [6].

For indoor maneuvering, The Stargazer sensor with ceiling landmarks (Hagisonic Company, Korea) are used with H20 mobile robots for moving between the adjacent labs. This guidance system inevitably causes positioning and orientation errors in front of the automated islands. The inaccuracy in robot pose is related to two reasons. The first is the strong lighting and/or sunlight, which blinds the stargazer and affects the identification of ceiling landmarks. The second reason is related to the accumulation errors of the odometry system. This system has encoders mounted on the robot wheels to provide feedback information of robot motion. Several reasons are responsible for creating accumulated errors like different wheels' diameter, wheel-slippage, wheels' misalignment and finite encoder resolution. According to the experimental results and previous studies, the rotation of the robot is the greatest factor for odometry errors [7], [8].

Related to the robot transportation, Hui *et al.* presented a single floor transportation system based on the H20 mobile robot [9]. In this system, the mapping and localization was completely based on Stargazer sensor module. Two hybrid methods are proposed for path planning from a single source to single destination points. To handle a complex building structure with laboratories distributed on different floors, a multiple floor transportation system has been developed [5]. In a mobile robot multi-floor transportation system, the robot onboard computer is developed to realize the functions of mapping, indoor localization, path planning, an automated door controlling system, communication system, battery charging management system, and an elevator handler system [10], [11].

Fig. 1. H20 mobile robot in front of the workstation

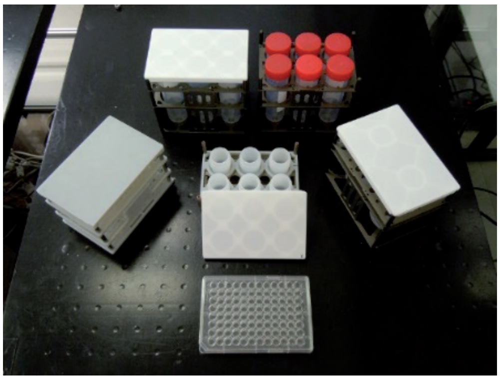


Fig. 2. Different labware and tube racks

The multi-floor environment adds more challenges for map-building since the map must represent positions in X, Y coordinates with floor numbers. In the developed mapping method [5], the SGM is used as a HEX reader in 'alone' working mode. The landmark ID is utilized to define the current floor. The information extracted from the IDs is used to build the relative map. Two kinds of mapping are employed which are relative map (metric map) and path map. The relative map is used as a global map in the multi-floor environment with a unique reference point. On the other hand, the path map is used to realize an obstacle-free set of paths between a starting position and the destination position. The path map relies on the relative map to specify a waypoint position inside it. A localization method based on the relative map is used to find the mobile robot's position inside the multi-floor environment [5]. A new static path method with a dynamic goal selection is designed to realize obstacle-free paths which direct the robot to the required goal. This method optimizes the planning speed as well as the number of paths used to reach the destination. However, the developed method cannot deal with unexpected dynamic obstacles. Thus, another path planning method is developed using a Floyd searching algorithm. This method is used, due to its efficiency and simplicity, to dynamically plan the path from any point to an intermediate destination [12]. The Floyd method is implemented when the dynamic obstacle avoidance integrated with the multi-floor system or if static paths become unavailable for any other reasons. A smart management system is created to select between these two methods so as to achieve high speed and flexible path generation.

To cope with the problem of robot positioning errors, an intelligent procedure to manipulate the required object and to correct the robot pose in front of the workstation is required. This is very crucial to guarantee secure and successful grasping and placing tasks for the labware. The robot has to be close enough to the workstation to ensure that the required target is within the reachable workspace of arms. This issue is also very necessary in case that the robot has unstable and weak arms. The optimal desired distance between the robot center and the manipulation point of workstation is 45 cm. The closer the robot distance is to this value, the better success rates for object manipulation can be obtained. Thus, the required distance range should be within ±2cm (43–47 cm) related to the optimal distance to obtain a sufficient success rate for labware manipulation.

In order to correct the robot position and to manipulate the required target, sensors for distance feedback are required. Visual, IR, and sonar sensors can be considered very useful for such tasks [13–18]. Visual sensors like 3D cameras are suitable and preferable since they provide position information related to the working space.

Using the visual sensors for position correction, the target reference in the image should be identified and localized. There are several features which can be used or extracted from the captured image to find the target. Color, shape, and textured features can be considered the most important sources for object identification. In order to use specific local textures, feature matching algorithms can be used. The local features have to be extracted and matched with the features in the database related to the object of interest. SIFT (scale invariant feature transform), SURF (Speeded-Up robust features), and FAST (Features from Accelerated Segment Test) are the most common algorithms for such purposes [19], [20], [21]. Theses algorithms are somehow independent to the changes in scale, illumination, and orientation. Katsuki *et al.* attached marks on the target objects to deal with them using robot system [22]. Zickler *et al.* used humanoid robots to achieve detection and localization of multiple objects on the kitchen desk [23]. Anh *et al.* proposed an object tracking method based on SURF [24]. Some researchers use the Kinect as a visual sensor for providing position feedback for the view. The Kinect sensor is very preferable since it provides directly the depth data without implementing any steps in image processing as in the case of stereo vision. Chung *et al*. used the Kinect sensor to help humans in object transportation with service mobile robot [1]. RAMISA ET AL. used the Kinect for cloth manipulation by depending on the depth frames [25]. According to the previous mentioned researches, the target detection and localization are essential to guide the mobile robot to achieve the required tasks. The target position can be used as a reference for arm manipulation and robot position correction tasks.

In this work, five H20 mobile robots are used for maneuvering between the laboratories for transporting multiple labware. Several concepts and challenges are taken into consideration to realize an efficient performance. The information feedback from multiple sensors improves the accuracy of labware manipulation and transportation. Sonar sensors are used for robot distance and orientation correction. Also, the Kinect V2 with speeded-Up robust features algorithm (SURF) is used to recognize and localize different object for manipulation and position correction purposes. In this paper, a position error management system is developed. The Stargazer sensor module is firstly used to reach the destination position. The main limitation of the Stargazer sensor is the complex building structure (transparent and the reflective surfaces) which directly affects its performance. Thus, a fine correction method is utilized to realize a stable performance when the error is less than 10 cm. Finally, a robot localization using Kinect sensor with the magnetic encoder is used to improve the robot positioning accuracy in front of the workstation.

This paper is organized as follows: in section 2, the parts of multi-floor transportation system are presented. The localization with error management of landmark reader is given in sections 3 and 4 respectively. Section 5 shows the manipulation of multiple labware which will be followed by the strategies of robot position correction. Finally, the results are concluded and discussed.

2. Multi-Floor Transportation System

The multi-floor system was developed to execute the transportation task in multiple floor environment. It includes mapping, indoor localization, path planning, automated doors management system, arm control and multiple labware manipulation, elevator handling, and collision avoidance as shown in Fig. 3.

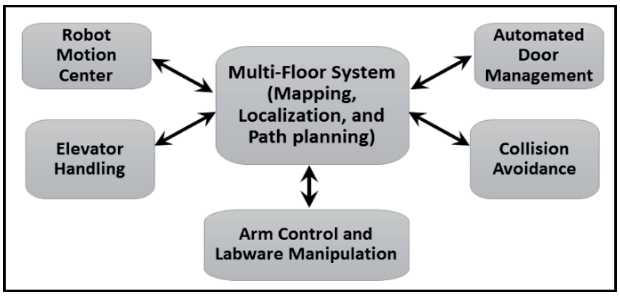


Fig. 3. Main parts of multi-floor transportation system

Multiple labware transportation requires robot maneuvering between different automated islands, laboratories, and floors. It requires also a cooperation between different stationary robots and mobile robots. To cope with these issues, an appropriate management system is developed. The hierarchical workflow management system (HWMS) controls the workflow with scheduling and distributing the transportation tasks [26]. The workflow management system sends the plan to the mobile robot transportation system as shown in Fig. 4. The plan includes the information related to starting station, end station, and the required labware to be transported. The labware transportation system includes 3 main parts: the robots management, the multi-floor system, and the grasping/placing system. The grasping/placing system is separated into two parts, object identification and localization and the arm control. The object identification and localization software with the visual sensor is utilized to recognize the target and to estimate its pose. The pose information is sent to the arm kinematic control and to the navigation system.

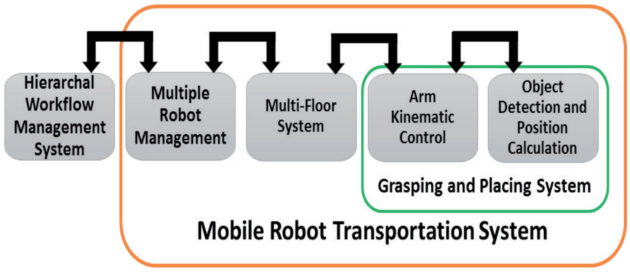


Fig. 4. Structure of mobile robot transportation system

3. Localization Sensor

Localization is considered the key point for mobile robots and can be defined as estimating the absolute or relative position. Many indoor localization approaches can be utilized for mobile robots. Each indoor localization method has its advantages, disadvantages, and limitations. For example, dead reckoning methods have the advantage of being simple and cheap and require a relatively short time for robot indoor localization. [27]. However, a positional error will accumulate over time, and thus they are unsuitable. RFID reader and IC tag methods are robust but unsuitable for large environments due to the expensive installation of IC tags [28]. Image vision methods give the robot accurate information about its environment [29] but fail to work properly in low light levels with certain complex situations. In addition, the required time is not satisfying. Methods using multiple sensors may be efficient and stable [30], [31]. But, the sensors could affect each other if they are employed in large areas.

In comparison with other existing indoor localization techniques, methods using artificial landmarks are somehow not very sensitive to lighting conditions. These methods are relatively easy to install, to maintain, and can cover large areas. Artificial landmarks have their advantages, in comparison with natural landmarks, of allowing a flexible and robust navigation system to be built. Passive landmarks are preferred over active landmarks due to their low cost, with the facility of installation and maintenance (no wires are required). They do not require a power supply and have the ability to cover a large area. Thus, passive artificial landmarks are utilized with a Stargazer sensor module (SGM) for indoor localization in this application. The SGM can recognize 4,096 landmarks and each landmark can localize 1.6–6.5 m in a diameter based on the ceiling height. Therefore, it can cover an area of 4,096*landmark range. The SGM is a low-cost localization sensor for large indoor environments which is accurate, robust, and reliable [32]. Fig. 5 shows artificial passive landmarks installed on the ceiling of life sciences laboratory. The SGM sensor works in two modes which are mapping and alone mode. In mapping mode, the SGM requires the configuration of map size, reference landmark, and type of landmark. Map building is then easily achieved by moving the SGM around the building to collect information on the relationships between landmarks. Information acquired from the ceiling landmarks gives the robot the ability to localize itself on the map according to the landmark's reference position. This working mode cannot build more than one map since it uses only an x and y position.

In this application, the SGM is used as a HEX reader in 'alone' working mode. The landmark ID is utilized to define the current floor where the information extracted with the IDs is used to build the map. There are some restrictions that prevent the stargazer sensor to be accurate enough for multiple labware transportations. These restrictions are related to its unstable behavior in special conditions such as the navigation with transparent/reflective surfaces and/or with low robot's battery voltage. Thus, an error handling management system is utilized to deal with the incorrect landmark readings. On the other hand, the fine function method is developed to overcome the shifting errors from Stargazer module readings (less than 10 cm) usually caused by increasing the robot speed, and wheel slipping. Finally, a robot positioning approach based on the target position using Kinect vision sensor and a motor encoder is employed to handle the positioning errors near the labware station.

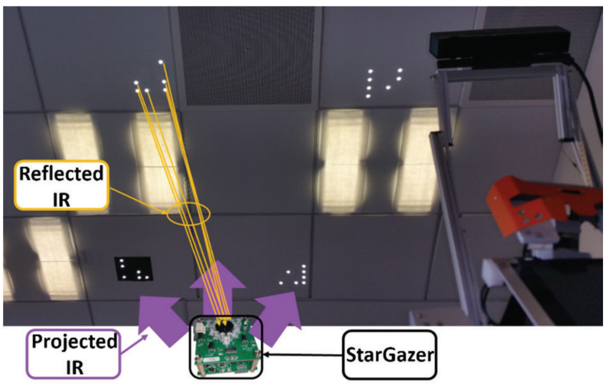


Fig. 5. StarGazer localization sensor

4. Landmarks Reader Error Management

The SGM reading collects errors which occur while the robot is moving in a complex environment. These

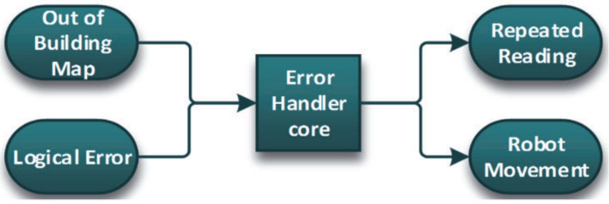


Fig. 6. Vision landmark reader error handling

errors are resulted from, for example, reflection or direct strong light and sunlight. The error handling for the SGM was developed to overcome these problems of incorrect readings to adapt with multiple labware transportation tasks. Fig. 6 shows the system, which mainly consists of the error handling core which is responsible for analyzing input error and choosing the actions required for error handling. Two scenarios can be performed in the case of error detection. Firstly, the SGM could repeat the ID readings ten times to eliminate the wrong ID. Secondly, the robot could move backward or forwards till realizing the right ID. The system detects a wrong ID reading if the SGM reads a non-stored landmark ID or if the calculated distance to reach the next position is larger than the normal distance. For example, if the reading for the next position is 10 m while the specified distance between waypoints is 3 m on average.

The error handling core continuously monitors these two expected input errors. If the system detects any error, the first scenario is to keep reading until the correct ID is received. Usually, the SGM error handling works well by suspending the robot's movement until the right reading is received. But, this way may take a long time or might even fail, especially in the glassy elevator environment where many light reflection occurs. Fig. 7 shows a reflection of a landmark appeared on the elevator's glass walls. These delays may significantly affect the whole time required to execute transportation tasks. This problem was resolved by specifying the number of repeat attempts as ten successive wrong readings. The second scenario described above starts immediately when the first has failed. The error handling system controls the robot in moving in the backward (BW) or forward (FW) direction with rotation (ROT) until the correct ID is received. This action is repeated five times as maximum range and in each

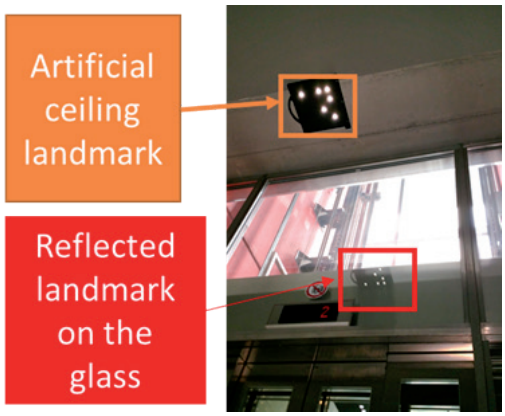


Fig. 7. Reflective ceiling landmark on the glassy wall

time the first scenario is performed until identifying the right ID. Fig. 8 shows the implemented method for correction by movement, while the error handling core scenarios are shown in Fig. 9.

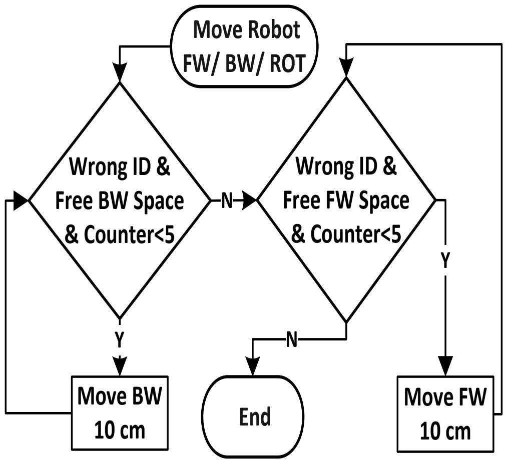


Fig. 8. ID reading correction by movement

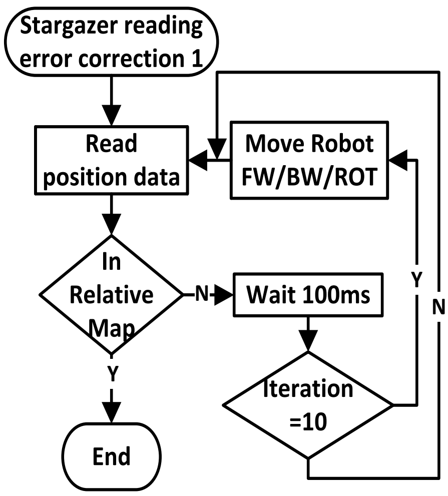


Fig. 9.a. Error management (ID is out of relative map)

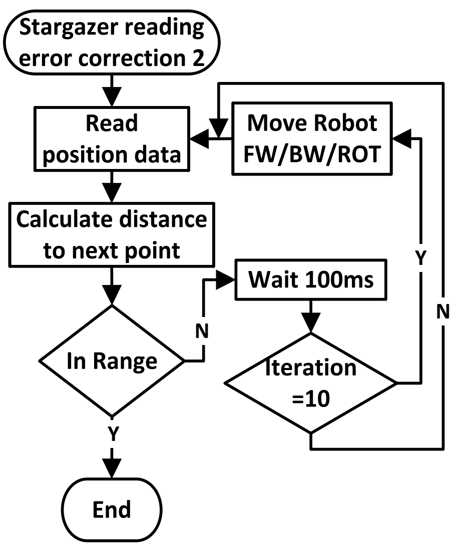


Fig. 9.b. Error management (ID is in relative map)

5. Multiple Labware Manipulation

The success of multiple labware manipulation depends significantly on 3 main aspects: the accuracy of robot positioning, the accuracy of arm control, and the accuracy of recognition with position estimation of the required labware. According to the arms workspace of the H20 robot with the workstation structure, each arm can manipulate two labwares alongside each other as shown in Fig. 10. The workstation has a length of 110 cm and it consists of 8 locations of labware containers. This requires two positions for the mobile robot to manipulate all locations. The shift distance between these two positions of robot is 29 cm. The required labware has to be identified and localized wherever it is located and the robot has to change its position for this purpose. The position of the target is used to guide the robotic arm. This requires an arm control based kinematic model to calculate the required joints' values. The kinematic model of H20 arms has been developed and applied physically on the system of H20 arms to guide them to the target [33], [34].

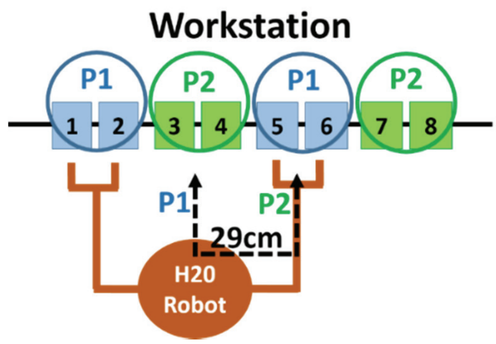


Fig. 10. Workstation structure for multiple labware

5.1. Visual Sensor for Labware Manipulation

Different visual sensors can be used for such tasks like stereo vision and 3D camera. The Kinect sensor V2 is considered as an optimal solution because it directly provides the depth information. Also, its cheap price (≈150 €) makes it very attractive for such applications. Kinect V2 uses 'time of flight' technology to provide the depth data. It indirectly measures the pulses time of laser light to travel from the projector to a target surface, and back to the sensor. The Ki-

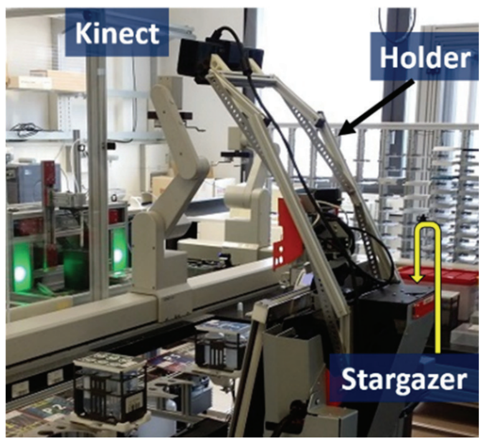


Fig. 11. Kinect holder fixed on the H20 body

nect sensor V2 has been fixed on the H20 body using a holder with a suitable height and tilt angle to provide a clear view for the automated island as shown in Fig. 11.The distance between the Kinect on holder and the workstation has to be carefully configured where the minimum depth value of Kinect V2 is 50 cm. The Kinect holder should not obstruct the head movement and stargazer FOV (see Fig. 11). A 12 V battery with current-voltage stabilizer is installed on the H20 body to supply the Kinect with the required power as shown in Fig. 12.

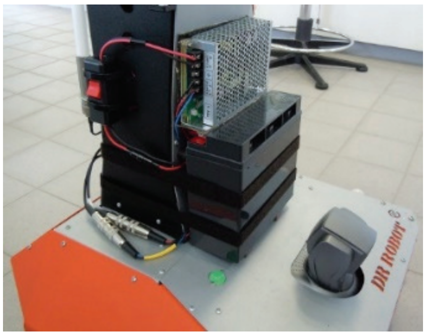


Fig. 12. Battery and stabilizer for Kinect sensor

5.2. Grasping and Placing Operations

For grasping and placing tasks with mobile robots, different grippers and labware containers have been designed [34], [35]. The designs have to be selected very carefully to guarantee a secure manipulation. Fig. 13 shows the final designs of the gripper and how it grasps the labware container.

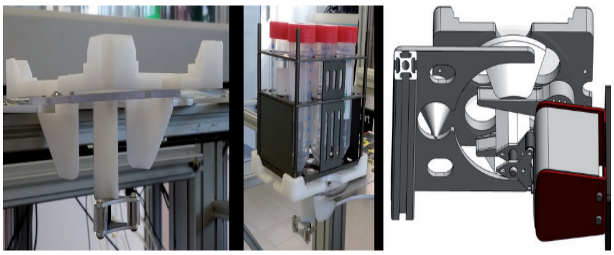


Fig. 13. Design of gripper and labware container

Different strategies have been applied to perform multiple labware manipulation [35]. According to the holders' appearance shown in Fig. 14, it is complicated to differentiate them. Also, the existence of a labware on the holder complicates its identification for the grasping task. To cope with this issue, 2 labels are used as a reference for each robot position as shown in Fig. 14. Each label is recognized and localized using Kinect V2 with SURF algorithm [36]. Each label position is used as a visual reference for 4 holders to achieve the grasping and placing operation. The label recognition is assigned by drawing a polygon around it with a cross to specify its center point to obtain its position. The recognition process starts with an offline step by saving the target image in the database as a matching reference. Since the Kinect sensor provides the depth data directly, it is simple to find the position of any point in the view. The workflow management system sends the order (grasp/place) with the holder number to the mobile robot transportation system. The limitation with this strategy is that all holders' positions related to each other and to the labels have to be identical for all other workstations. For this reason, a specific label has been attached to each holder as shown in Fig. 15.

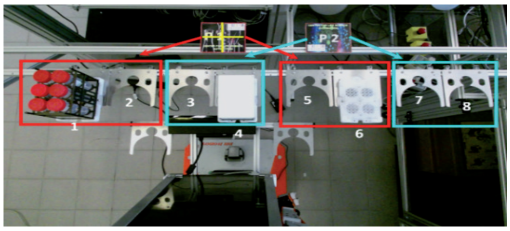


Fig. 14. Label for each position of robot manipulation

Fig. 15. Label for each holder on the workstation

To grasp the required labware, it is better to track it directly to avoid any manipulation mistake. Since the labware have transparent or white lids (see Fig. 2) for protection from cross contamination, it is not possible to identify them. Therefore, a specific label has been attached on each labware lid for the identification process as shown in Fig. 16. The label contains the labware information with a particular number for classification purposes. The required time for performing the grasping operation is about 69 seconds while 59 seconds are required for the placing operation [35]. Fig. 17 shows the grasping operation for the labware and how the robotic arm places it on the H20 holder for transportation task.

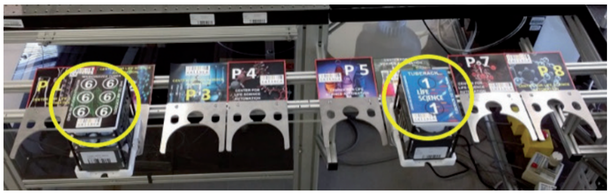


Fig. 16. Labware label on lid for identification process

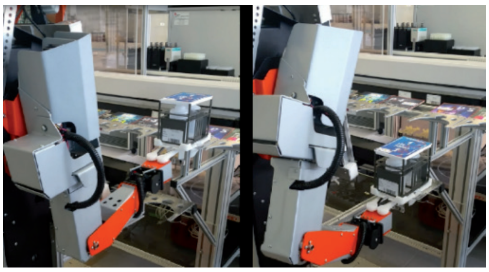


Fig. 17. Grasping operation for the required labware

It is possible to use just numbers, characters or barcode for labware identification and manipulation. But the use of labels is still better and more helpful. The labware/holder information with a background picture in the label gives adequate features. These labels are not used just for identification, but for position estimation also. These labels can be recognized under strong lighting conditions and even when they are partially occluded by some object as shown in Fig. 18. This can be considered as one of the advantages of using this method. It is still possible to grasp the required labware even if the related label is partially seen by the visual sensor.

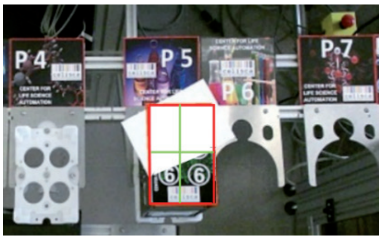


Fig. 18. Label recognition with partial occlusion

5.3. Problem Description of H20 Arms

The H20 robot has unstable arms with weak joints where the joints compliance causes positional errors especially for the case of dealing with wide workstation. The gravity with payload increases the elasticity of each joint [37]. There are some other reasons of imprecision like the resolution of the DC servo motors with control system and the imprecision of the mechanical linkages. Also, the friction, temperature, and manufacturing tolerances play a role in arm positional errors. The accuracy of H20 arms has been checked according to the grasping configuration which is shown in Fig. 19. The arm end effector has been moved to be at the height of Y=180 mm at different distances (Z-values) between the shoulder and end effector. Table 1 shows in millimeter the error value in Y-axis at each Z value. It is clear that the Y-error increases by increasing the Z value. This is related to the unstable and weak joints with the other reasons

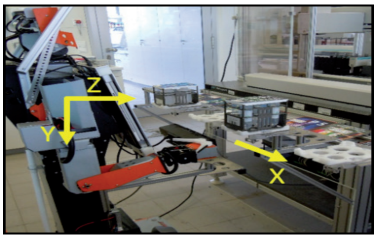


Fig. 19. Grasping order and shoulder coordinates

Table 1. Position error of end effector in Y-axis

Z values (mm)	350	380	400	420	440	450
Y-error (mm)	15	20	25	35	45	50

which are previously mentioned. Also, it is important to mention that these error values are without dealing with any extra weight. It means that the arm positional errors will increase after dealing with labware which their weight range are between (200 g – 800 g).

Dealing with such robotic arms requires more efforts and processes which have to be performed to decrease the errors. Using the hand camera can be one of the solution as shown in Fig. 20. The Intel RealSense F200 camera, which is a 3D camera, can be used for labware grasping. Specific marks or barcodes can be identified and localized to guide the robotic arm and to correct the end effector position. This methodology requires the installation of a hand camera for each arm. Also, it is not possible to use the hand camera in the placing task because it is not possible to identify the holder label due to two reasons. The first is the posture of holder label which is in parallel with the view direction of the hand camera. The second reason is related to the existence of labware in front of the hand camera. This labware blocks the camera view during the placing task. The other methodology, which can be used to decrease the arm positional error, is to track the end effector during the movement operation as shown in Fig. 21. This approach requires to fix a label at each hand for position tracking. The real time tracking for the hand during the approaching process is computationally intensive. It requires more data processing and time which burden the CPU and memory. To cope with all these issues, the robot position has to be corrected. Moving the robot closer to the workstation will decrease the positioning errors of the arm end effector and will improve the success rate of grasping and placing operation. Distance correction is very necessary especially for the placing tasks due to the labware weight which increases the positional errors.

Fig. 20. Intel RealSense F200 camera for grasping task

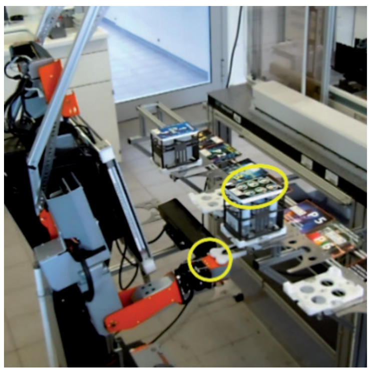


Fig. 21. End effector tracking in grasping task

Related to the robot orientation, sometimes the robot is not straight enough in front of the workstation. For this case, the orientation angle of the target related to the robot can be calculated. This angle leads the robotic arm to manipulate the target in the right way. For calculation of orientation angle, coplanar POSIT algorithm, which stands for POSe Iterations, can be used [38]. To use this algorithm, the target has to be previously known. The positions of target corner points related to its center have to be calculated according to the real physical coordinates. Also, these corner points have to be found in the image coordinates as shown in Fig. 22. The H20 arms are not stable and accurate enough to be used with this algorithm. Also, the H20 arm doesn't have a spherical wrist which simplifies this kind of manipulation. Therefore, the more direct way to deal with this problem is to correct the robot orientation in front of the workstation.

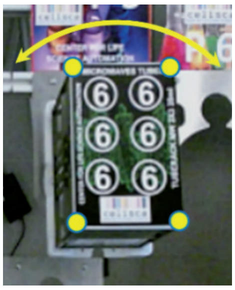


Fig. 22. Orientation angle for labware manipulation

6. Position Correction Strategies of Robot

6.1. Fine Position Correction Method

In laboratory automation, a high transportation speed over large areas is important to minimize the required time for the whole laboratories operation. Moving at a high speed using H20 mobile robots adds challenges related to the inaccuracy of movement. The fine correction function is used to increase the robot's position accuracy at higher speed during multiple labware transportation tasks. The robot linear velocity was increased by 20% to reach 0.2 m/sec while increasing the rotation velocity was adapted with the required rotation angle degree to get the balance between speed and accuracy. For example, if the rotational angle required is more than 30 degrees, then the highest rotation speed of 0.34 rad/sec is used. For a lower angle, the angular speed will be decreased to achieve the highest accuracy.

The fine positioning method was developed to overcome this problem and to achieve a higher positional accuracy. This method uses two techniques. Firstly, the robot's speed is controlled in order to minimize movement error caused by wheel slip and to give more time for the motor encoder to be read and updated. Secondly, a position correction is added in the X or Y direction (depending on the latest movement) as shown in Fig. 23. The H20 robot has a differential driver, and thus it is not easy to correct its

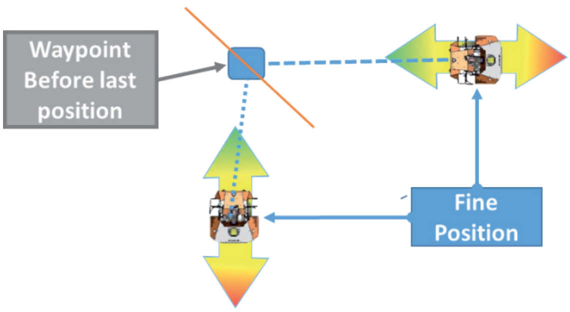
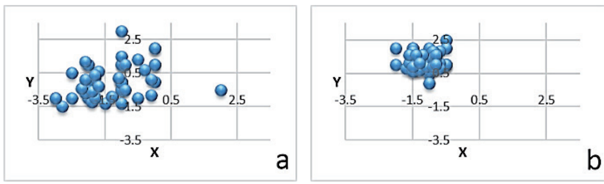


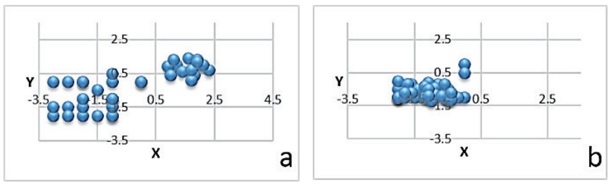
Fig. 23. Fine position correction based on last direction

position in the right/left position. Thus, the fine positioning method records the direction of the last movement and utilizes this direction to correct the robot's position until reaching the motor accuracy limitation which is 1 cm.

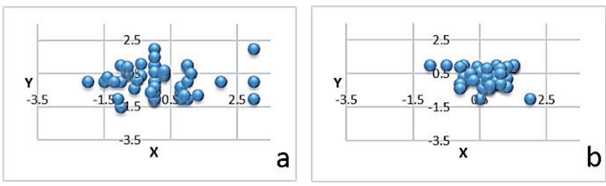
Experiments were conducted to determine the repeatability of robot positioning at different grasping, placing and charging stations before and after employing the fine position correction method. These tests have been performed 50 times in multiple floor environment. Each time the robot moves from the charging station towards the grasping station. Then, it moves to the placing station and finally returns to the charging station. In these experiments, a 100% success rate was achieved. Fig. 24 clarifies the repeatability tests of the mobile robot's position at the important stations in the transportation path. In Fig. 24, group (a) and (b) represent the repeatability without and with using fine function respectively. In comparison between groups (a) and (b) in Fig. 24, it can be noticed that the precision and repeatability results have been improved in the required positions after using fine correction method. In the grasping position (see Fig. 24 (Test 1)), the repeatability range has been improved from 5 cm to 1.5 cm in the x-axis. To improve the positioning accuracy in the transportation path, calibration processes have been performed at the important stations. Table 2 reported the repeatability, and standard division of robot positioning. Table 3



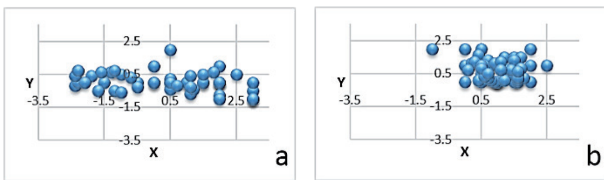
Test 1: repeatability at grasping position.



Test 2: repeatability at placing position.



Test 3: repeatability at robot charging position.



Test 4: repeatability at elevator position.

Fig. 24. Contrast experiment for fine method

shows an example of the consumed time for mobile robot transportation between two stations with and without fine correction method. The time has been reported for 50 times of transportation in multiple floor environment.

Table 2. Comparison of repeatability results in cm

		Without Fine Method		With Fine Method	
	Axis	**S.D**	**Repeatability**	**S.D**	**Repeatability**
Grasping point	X	0.95	±2.5	0.38	±0.75
	Y	0.92	±2.25	0.51	±1.3
Placing point	X	0.67	±1.5	0.58	±1
	Y	0.65	±1.25	0.43	±1.1
Charging point	X	0.95	±2	0.68	±1.75
	Y	0.58	±1.5	0.64	±1
Elevator point	X	1.05	±2.5	0.59	±1.5
	Y	0.82	±1.75	0.53	±1

Table 3. Consumed time for mobile robot (in minutes)

Without Fine Method			With Fine Method		
Min	Max	Av	Min	Max	Av
13:22	17:20	15:32	10:46	12:44	11:26

6.2. Position Correction Based on Sensors

In this section, two kinds of sensors are used to correct the robot position, sonar sensor and Kinect sensor. The information from these sensors can be used as a feedback to correct the robot position and orientation in front of the work station. Fig. 25 shows the system architecture of robot pose correction.

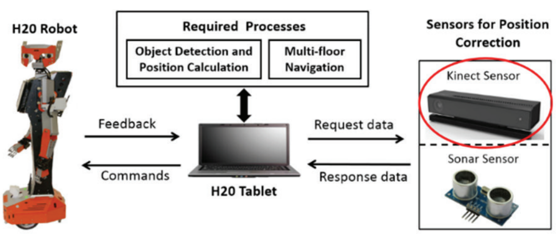
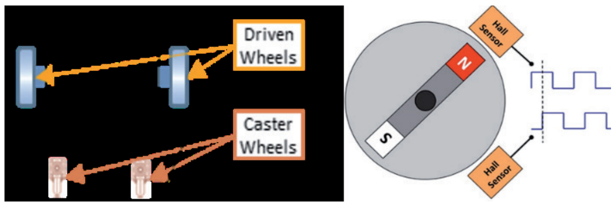


Fig. 25. System architecture of robot pose correction

The H20 robot has a non-holonomic wheeled mobile platform which has driving and castor wheels (see Fig. 26.a). The driving wheels are driven by motors, so the robot can either move forward, backward or rotate around itself. Two EMG49 motors are used to drive the mobile robot. This motor has a 24V DC motor, 980 pulses per rotation magnetic encoder (consist of rotary magnet disk and Hall Effect sensor as shown in Fig. 26.b), and 49-1 gearbox ratio. The H20 main onboard controller connected to Sabertooth which controls these motors. The Sabertooth dual motor driver board is used for providing the motor with the required voltage with a specific direction to turn the motor on/off. The movement based on encoders starts by converting the required distance to the number of encoder pulses. The wheel radius and the number of encoder pulses per rotation are taken into consideration to calculate the number of encoder's pulses as shown in Eq. (1),

$$No.\,of\ Required\ Pulses = \frac{D}{Wc*Wp} \tag{1}$$

where D is the distance in m, Wc is the wheel circumference, and Wp is No. of encoder pulses per wheel rotation. The navigation system sends the required distance with the movement direction (FW/BW) to the motion and power control which calculate the required encoder pulses.



a *b[39]*

Fig. 26. a: wheels platform, b: magnetic encoder

Two stages of robot position correction method based on the target location are performed as shown in Fig. 27. The first is implemented to correct the robot position in right/left direction. The workstation has 8 locations of labware containers and each arm of H20 robot can manipulate two locations alongside each other (see Fig. 10). Therefore, two robot positions in the right/left direction are required to manipulate all locations. The shift distance (SD) between these two positions is 29 cm. When the navigation system gets the SD value, special procedures are performed to correct the robot position based on the motor encoder. It starts with storing the current robot Orientation Angle (OA) and controlling the robot

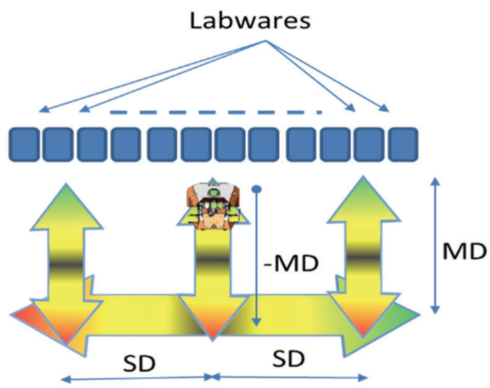


Fig. 27. Position correction directions

backward by specific Moving Distance (MD). Then, the robot rotates 90 degrees to right/left according to the required shift direction. Thereafter, the robot moves with SD value, rotates towards the station, and moves forward with MD value. The final step is to correct the robot orientation based on OA value using stargazer sensor. The second stage is to correct the distance between the workstation and the robot to obtain a sufficient success rate for labware manipulation. The desired distance range between the robot center and the manipulation point of workstation is 43–47cm.

6.2.1. Sonar Sensors

The sonar sensors can be used for different applications of mobile robots such as collision avoidance and distance detection. The distance data is precisely calculated by the time interval between the instant of sending the sonar signal and the instant when the echo signal is received. The front base of H20 robot has 3 built-in DUR5200 sonar sensors. One sensor is in the middle and the other two are on the left and right sides. The DUR5200 sonar sensor can detect the range information from 4 cm to 255 cm since the controller board uses only one byte to represent the distance. This means that if the range is less than 4 cm or more than 255 cm, it will be reported as 4 cm and 255 cm, respectively. These sonar sensors can be used to correct the robot distance to the workstation as shown in Fig. 28. Also, the robot orientation can be corrected to be straight by rotating the robot left/right till the reading form the two sensors on the left and right side are equalized. But this strategy of robot

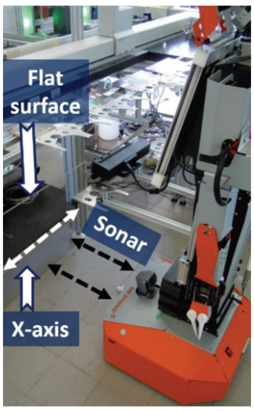


Fig. 28. Robot pose correction based on sonar sensors

pose correction is not reliable enough due to some reasons. Flat surface is always required to reflect the sonar signal. It is not possible in some stations to install such a surface due to the environment structure. Existence of obstacles in front of the sonar sensors leads to wrong estimation for the distance and orientation of robot. Also, this strategy lacks the positioning feedback in the X-axis (see Fig. 28). Therefore, using the Kinect sensor to provide feedback information is more reliable for robot position correction.

6.2.2. Kinect Sensor V2

The object detection and position estimation using Kinect V2 can be considered an efficient strategy to correct the robot position especially in front of wide workstation. The required label for grasping/placing has to be recognized first. Then, the position of label center point in the image coordinate is derived. This can be calculated using the corners' position of the label as shown in Fig. 29. In order to find the position of this center point related to the Kinect sensor, mapping processes have to be performed. Since the RGB frame and depth frame are not identical, the interested point in the RGB frame has to be mapped to its related point in the depth frame. Then, another mapping step is performed from depth frame to the Kinect space coordinates. The result of these mapping steps is the real position of the label center point related to the Kinect on the holder [36].

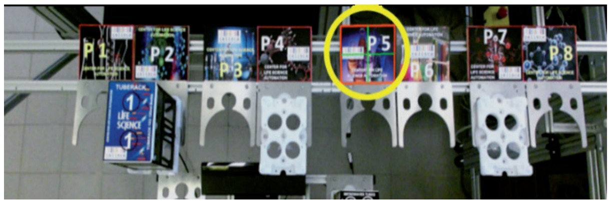


Fig. 29. Target recognition for position correction

The next important step is to apply the extrinsic calibration. The position information related to the Kinect camera has to be transformed to be related to the robot center point as shown in Fig. 30. The calibration from Kinect space to robot space includes the transformation in translation and orientation. This belongs to the difference in the position and the tilt angle (t) between the Kinect and robot space [35]. According to the distance between the Kinect on holder and workstation, the position precision which can be obtained from Kinect is about ±1 mm.

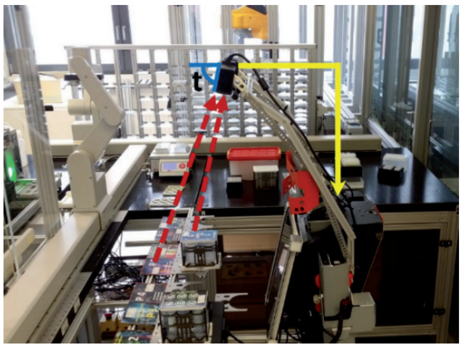


Fig. 30. Position calculation and extrinsic calibration

The position of target related to the robot center is used to correct the robot position. The position correction is applied in two direction: left/right (L/R) and FW/BW. The correction in FW/BW direction is very helpful to solve the problems of unstable and weak arms. On the other hand, the correction in left/right direction helps to deal with wide workstation. If the grasping operation is performed with a particular arm (right or left), the placing operation for the grasped labware has to be achieved using the same arm. For this case, the left/right correction is very required. The correction information is sent from the Kinect platform to the navigation platform through client-server model. Using this communication mod-

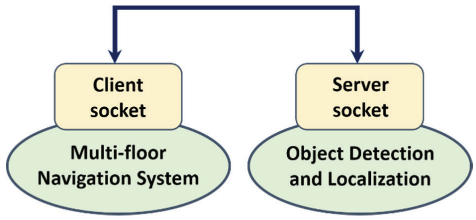


Fig. 31. Client-server model for system integration

Table 4. Tests results of distance correction

Distance (cm)			Number of times	Corr. status
Before corr.	After corr.	Errors		
42	45	-3	1	Yes
43	43	-2	1	No
44	44	-1	2	No
45	45	0	5	No
46	46	+1	2	No
47	47	+2	4	No
48	45	+3	5	Yes
49	45	+4	4	Yes
50	45	+5	3	Yes
52	45	+7	1	Yes
54	45	+9	1	Yes
60	45	+15	1	Yes

el, these parts can exchange the orders and information between each other as shown in Fig. 31. The client-server connection architecture module (asynchronous socket) is enabled to control the interaction of the navigation system with other sub-system over Ethernet. A TCP/IP command protocol based server-client structure is used to guarantee the reliability and the expandability. So any kind of devices can be added into the communication network conveniently with a new IP.

Table 4 shows the distance correction results of 30 tests based on Kinect V2 sensor. The table includes the robot distance values before and after the correction procedure. The optimal distance between the robot center and the manipulation point of workstation is 45 cm. However, the distance range should be within 43–47cm (±2cm) to obtain a sufficient success rate for labware manipulation. The robot doesn't need to correct its distance if it is within the desired range. Table 5 shows the overall success rate of the grasping and placing operation with and without distance correction. It can be clearly noticed that the success rate has been improved to reach 97% for the grasping and placing tasks. There are still 3% errors in the performance which belong to the instability of robot arms which have weak joints. Also, the low voltage of robot battery affects the manipulation performance. The re-

Table 5. Success rate of operations

Dis. Corr.	Attempts	Succ. Grasp	Succ. Place
No	50	92%	90%
Yes	30	97%	97%

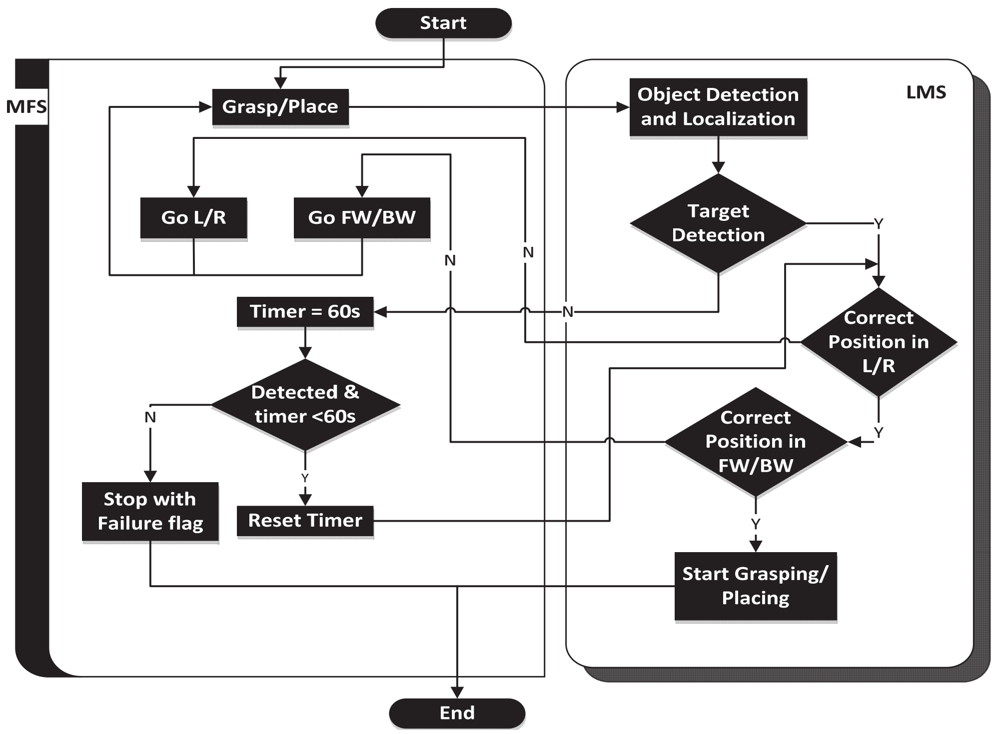


Fig. 32. Operation processes of the position correction in front of (Grasping/Placing) station

quired time (in seconds) for correction procedure can be calculated according to the following equation:

$$3+1.5+(Abs.(dis.\ error\ (cm))/8.3\ cm/sec) \quad (2)$$

where 3 seconds are required as delay time to be sure that the Kinect is not trembling and the robot is stable when it reaches the workstation. The 1.5 seconds of time is required for sockets communications, target recognition, position calculation, and sending the order to the navigation system. Finally, 8.3 cm/sec represents the linear speed of robot during the distance correction procedure.

Fig. 32 shows the flowchart of position correction with the communication process between multi-floor system (MFS) and labware manipulation system (LMS). This project work has been developed using Microsoft Visual Studio 2015 with C# programming language. The project is running on a Windows 10 platform in the H20 tablet.

7. Conclusion

In this paper, a new system for multiple labware transportations based mobile robot in life science laboratories is presented. To realize the required accuracy for multiple labware transportations based mobile robot, the Stargazer sensor as a low-cost and reliable localization module is used. Stargazer sensor module has unstable behavioral under direct sunlight and with reflective surfaces. Thus, a robot position error management and correction function are developed. In this paper, a hybrid approach for robot pose correction in life science laboratories has been presented. The problem statement with the proposed methodologies has been discussed. The hybrid strategy depends on using the fine method and Kinect sensor V2 with a motor encoder. The Kinect sensor can be considered one of the powerful 3D cameras which provides the position information in a fast way. Kinect V2 provides high resolution image, wide field of view, and accurate position data directly that makes it very desirable for such tasks. The client server model has been used to integrate and connect the identification and localization system with the navigation system. Two experiments are provided to validate the efficiency of the system and the new positioning strategy. The experimental results show that the proposed correction strategy has efficient performance, which meets all requirements to realize a successful multiple labware transportations based mobile robots in life science laboratories.

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