Automated Warehouse Material Handling using 3-Dof Robotic Manipulator Based on Computer Vision and Iot

Athul Zac Joseph, Renjith Joseph, Harikrishnan D, Sudheer A.P

Abstract: In this era of e-commerce and online shopping, the focus is on bridging the time gap between order and delivery of a commodity. Delay in warehouse material handling is one of the primary reasons responsible for this time gap which is only second to transportation delay. Conventional warehouses relying on workforce suffer from poor efficiency, high labour cost and unanticipated delays. Automated warehouses can increase productivity and reduce the cost associated with human operators. This paper focuses on automating the storage and retrieval of goods in a warehouse with the help of computer vision algorithms and Internet of Things (IoT). The goods are packed in colour coded boxes equipped with Radio Frequency Identification (RF-ID) tags storing the details of its contents. Cameras are placed at strategic positions in the warehouse which monitor the load pickup and unloading area. Smart inventory management is implemented by utilizing RF-ID tags and a database which keeps track of the movement of goods in the warehouse. The storage and retrieval operations in the warehouse are scheduled either using a smartphone application or a web page that can access the warehouse database. The system with some minor modifications can be used in shipping ports where large volumes of load are handled every day.

Index Terms: Computer Vision, IoT, Warehouse Automation, 3P Robotic Manipulator

I. INTRODUCTION

Cyber-physical systems form the core of industry 4.0, where automation, internet of things along with cutting edge technologies revolutionize manufacturing and production. Warehouses are an integral part of the supply chain and logistics which when automated can improve the critical time involved in the manufacturing and delivery of commodities. In the past, investments in material handling operations in a warehouse were of less significance since the additional cost involved did not add to the product value. With the online shopping platforms and merchandise competing to deliver goods to customers in minimal time, improving the material handling strategies in warehouses is a prime concern to the supply chain and logistics sector.Peter *et al.* [1] observed that the lead time of material handling in a warehouse is one of the factors contributing to the production lead time. Introduction of automation and database management using Internet of Things (IoT) in the warehousing sector is a viable solution to tackle the problem of the production lead time. Automation is the use or introduction of automatic equipment in a manufacturing process or facility [2]. The warehouse management system reflects the aspects of Industry 4.0 in which Cyber-Physical Systems are used to realize a digital and intelligent warehouse [3].Most of the research in the field of warehouse material handling to date are based on Automated Guided Vehicles (AGV). AGVs can be track based, wire guided, optical, infrared, laser or free navigation. Track based AGVs are not flexible once the tracks are installed in the factory while laser guided AGVs suffer from high cost of production [4]. Patil *et al.* [5] presented the idea of an automated robot for warehouse using image processing in which shortest path calculation and obstacle detection are performed in MATLAB using camera feed. Mehmet *et al.* [6] proposed the use of a fleet of robotic forklifts wirelessly operated from a centralized supervisory controller for warehouse automation. These systems require manual supervision which will increase the cost of operation. The drawbacks of AGVs include high initial investment, lower payload capability and inability to perform vertical stacking. Proper inventory management techniques can improve the productivity of a warehouse. Burton I Zisk [7] suggested that the data acquired for system direction such as next destination and quantity being handled can be used to maintain inventory records automatically. Efficient inventory control in a warehouse is possible with the use of radio frequency identification (RF-ID) tags, automatic identification (Auto-ID) sensors, wireless communication networks and indoor warehouse management systems. Passive RF-ID tags have an inherent advantage of reusability, and they get powered by the electromagnetic field of the RF-ID reader. Saleh *et al.* [8] conducted a feasibility study of RF-ID based data management system and inferred that such systems could reduce human intervention thereby increasing productivity. Internet of Things and smartphone applications add value to the database management system.

The Automated Warehouse Material Handling System (AWMHS) relies on image processing techniques for the detection and tracking of colour coded containers. A Raspberry Pi 3B lies at the heart of the entire system.

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Cameras placed at predetermined locations overlooking the loading and unloading area send the real-time feed to the Raspberry Pi. The goods arrive at the warehouse in colour coded boxes with an RF-ID tag storing information about its contents. The algorithm running on Raspberry Pi differentiates between the goods based on the colour. A 3-DOF serial manipulator equipped with a pneumatically actuated picking mechanism facilitates the movement of goods in the warehouse. The entire floor area of the warehouse forms the workspace of the manipulator which also facilitates the movement of goods based on the camera feedback. The picking mechanism has an RF-ID reader attached to it, which when picking the box, updates the warehouse inventory database hosted in the Raspberry Pi. The warehouse inventory database keeps track of arrival time, the location, and contents of the container. This warehouse inventory database is used for scheduling the dispatch operations in the warehouse. The database can be accessed over a web page. A smartphone application is used to monitor and schedule the storage and dispatch operations in the warehouse. Hence AWMHS encapsulates material handling and inventory management effectively.

II. MODELLING OF 3P MECHANISM

A. *Kinematic Modelling*

Kinematic modelling is used to establish a relationship between the joint parameters of the manipulator and the pose of the end effector. It is required to control position and orientation of the end effector in 3-D space so that it can follow a defined trajectory or manipulate objects in the workspace [9].

B. *Denavit-Hartenberg Modelling of Material Handling System*

The material handling system which handles the pick and place operations can be modelled as a 3 DOF serial manipulator (3P) with dimensions 100cm × 60cm as shown in Fig. 1. The system has three stepper motors driving the end effector using a belt and pulley mechanism. Each this stepper motor driven belt and pulley mechanism can be modelled as a prismatic joint. In this section the Denavit-Hartenberg (DH) parameters for the AWMHS is calculated in Table. I. Frame assignment for the mechanism is shown in Fig. 2.

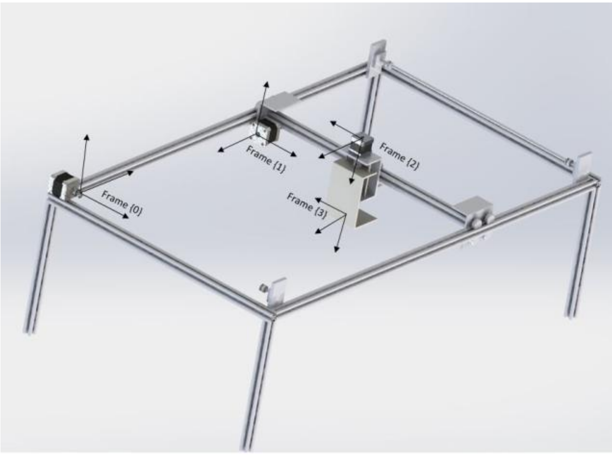

Fig 1: Scaled model of mechanism

Table. I: DH parameter table

Joints	θ_{n+1}	d_{n+1}	a_{n+1}	α_{n+1}
1	0	d_1	0	-90
2	-90	d_2	0	90
3	0	d_3	0	0

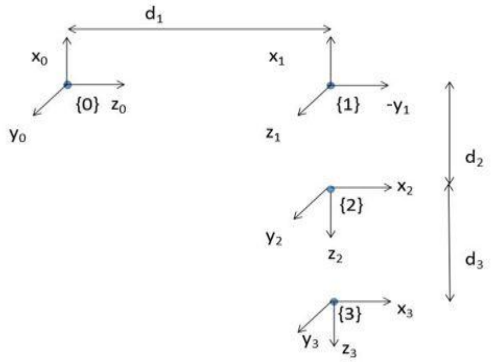

Fig 2: Frame assignment for 3P manipulator

The final transformation matrix of the end effector pose with respect to the base frame is given in (1).

$$ {}^{0}T_3 = \begin{bmatrix} 0 & 0 & -1 & -d_3 \\ 0 & 1 & 0 & d_2 \\ 1 & 0 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1) $$

Jacobian of the 3 DoF manipulator which may be used for mapping between joint velocities and end effector velocity is given in (2).

$$ J = \begin{bmatrix} J_1 & J_2 & J_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \quad (2) $$

The end effector velocities in terms of joint velocities are given in (3).

$$ \begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = \begin{bmatrix} 0 & 0 & -1 \\ 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} \dot{d}_1 \\ \dot{d}_2 \\ \dot{d}_3 \end{bmatrix} \quad (3) $$

Static Structural Analysis

Static analysis was used to analyse the effect of the application of a force on a static body. The frame of the AWMHS was subjected to a force equal to the weight of the box when it tries to lift the box off the ground. A mass of 1.5kg would result in 15N force acting downwards on the picking mechanism. This was simulated in ANSYS to obtain the deformation the

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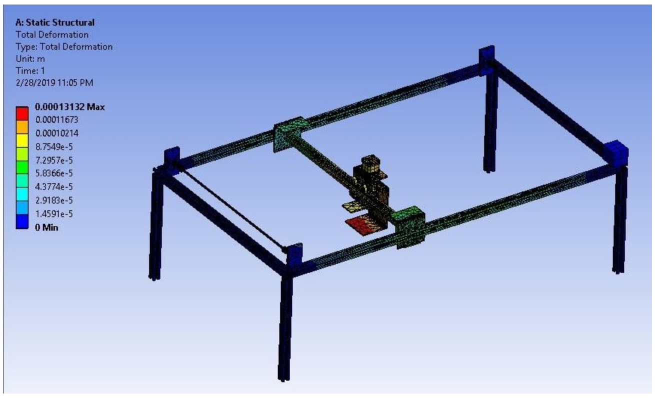

Fig. 3: Total deformation analysis in ANSYS.

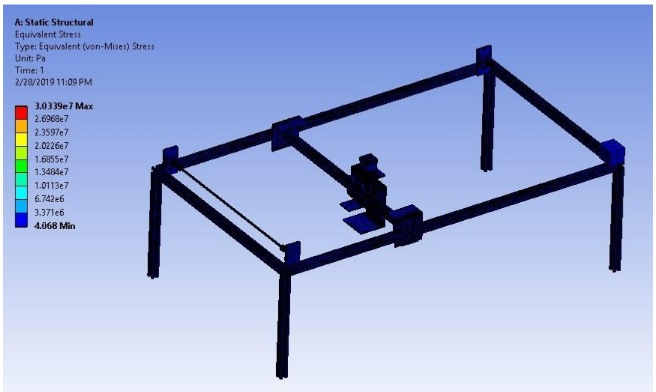

Fig. 4. Equivalent Stress analysis in ANSYS.

scaled down model of AWMHS would be subjected to in a real world scenario. Fig. 3 shows that the maximum deformation in the structure was found to be 0.131mm. The peak stress that the structure was subjected to was found to be 30.3MPa (Fig. 4.). The yield strength of aluminium used for fabrication is 280MPa. Table. II gives the material properties of the aluminium used for fabricating the structure.

C. *Dynamic Modelling*

Dynamic modelling is used to determine the force and torque requirements of the joint actuators which are the motors driving the belt and pulley mechanism in this case. Using Lagrangian approach (4),

$$\begin{bmatrix} F_1 \\ F_2 \\ F_3 \end{bmatrix} = \begin{bmatrix} m_1+m_2+m_3 & 0 & 0 \\ 0 & m_2+m_3 & 0 \\ 0 & 0 & m_3 \end{bmatrix} \begin{bmatrix} \ddot{d}_1 \\ \ddot{d}_2 \\ \ddot{d}_3 \end{bmatrix} - \begin{bmatrix} 0 \\ 0 \\ m_3 g \end{bmatrix} \quad (4)$$

The joint variables d_1, d_2, d_3 are considered as cubic spline functions of the form (5).

$$\begin{aligned} d_1 &= a_{01} + a_{11}t + a_{21}t^2 + a_{31}t^3 \\ d_2 &= a_{02} + a_{12}t + a_{22}t^2 + a_{32}t^3 \\ d_3 &= a_{03} + a_{13}t + a_{23}t^2 + a_{33}t^3 \end{aligned} \quad (5)$$

The following boundary conditions were considered to determine the joint variables. All the joints have initial and final velocities equal to zero. The mechanism moves from its initial position to the final position in 4 seconds. The first two joints have a displacement of 0.376m and the third joint has a displacement of 0.08m. The joint variables are obtained as functions of time in (6). Fig. 5 and Fig. 6 shows the displacement, velocity and acceleration of each of the joints obtained using MATLAB.

Table. II: Materials properties of Aluminum alloy

Property	Value
Density	2770 kg m^{-3}
Coefficient of Thermal Expansion	2.3×10^{-5} C^{-1}
Specific Heat	875 J kg^{-1} C^{-1}
Compressive Yield Strength	2.8×10^{8} Pa
Tensile Yield Strength	2.8×10^{8} Pa
Tensile Ultimate Strength	3.1×10^{8} Pa
Zero-Thermal-Strain Reference Temperature	22 C

$$\begin{aligned} d_1 &= 0.0705t^2 - 0.1175t^3 \\ d_2 &= 0.0705t^2 - 0.1175t^3 \\ d_3 &= 0.015t^2 - 0.0025t^3 \end{aligned} \quad (6)$$

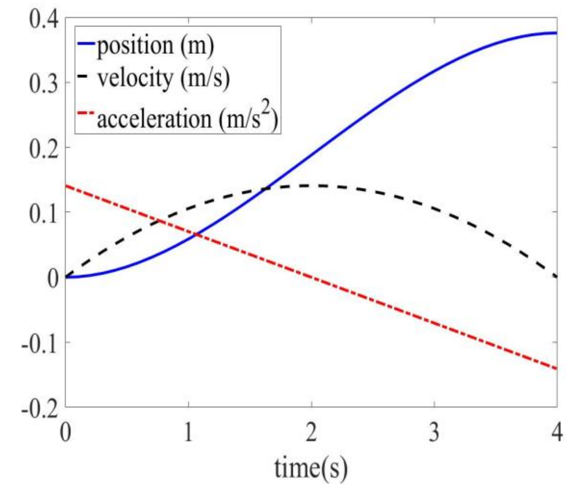

Fig. 5. Parameters (displacement) of joint 1 and 2.

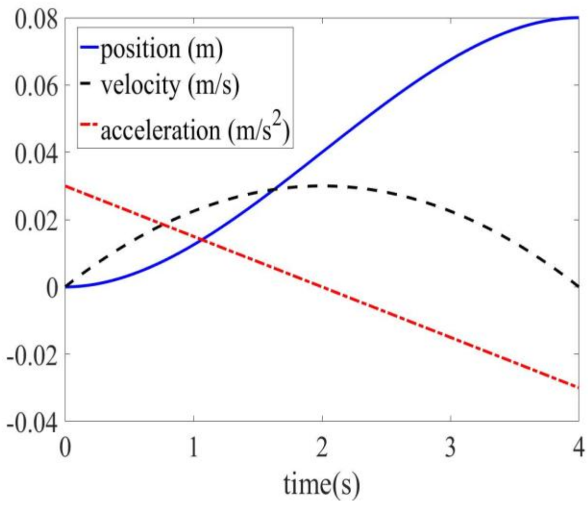

Fig. 6. Parameters (displacement) of joint 3.

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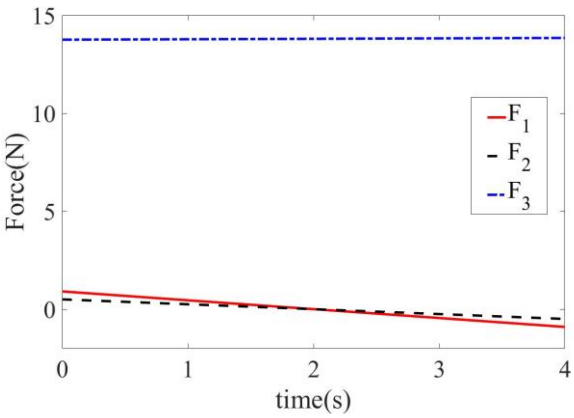

Fig. 7. Forces at the joints.

The SolidWorks simulation software was used to determine the masses m1, m2 and m3 as 2.875kg, 2.0525kg and 1.5kg respectively for a payload of 1.5kg. Using (4) and (6), the forces acting at the joints were calculated in (7).

$$\begin{aligned} F_1 &= 0.906 - 0.453t \\ F_2 &= 0.5 - 0.25t \\ F_3 &= -13.755 - 0.0225t \end{aligned} \tag{7}$$

The maximum values of the forces were obtained as 0.906N, 0.5N and 13.845N respectively from Fig. 7. The motors at the first two joints use a belt and pulley mechanism with 6mm pulley radius and the third motor uses a lead screw arrangement with a radius of 4mm. So the maximum torque required to drive the mechanism at the joints 1, 2 and 3 were calculated as 0.055kgcm, 0.031kgcm and 0.564kgcm respectively.

III. METHODOLOGY

A Raspberry Pi 3B forms the central processing core of the proposed mechanism. The unloading zone of the warehouse is monitored by a USB camera mounted vertically above it providing a live feed to Raspberry Pi. Python script has been developed for detecting the Colour coded boxes arriving at the unloading zone. Raspberry Pi controls the stepper motors to move the end-effector towards the object to be picked up. The end effector is a pneumatically actuated picking mechanism which moves in a cuboidal workspace. RF-ID reader incorporated into the picking mechanism reads the RF-ID tag on the object and updates the Warehouse inventory database hosted by the Raspberry Pi. Once the object is picked up, the python script searches the Warehouse inventory database and finds its storage location. This triggers the end-effector to move towards this desired location and drops the object. The above steps are repeated until all the boxes are transferred to the desired storage locations. Fig. 8 shows the various processes that constitute the system. Fig. 9 shows the communication between Raspberry Pi and various components in the system.

A. *Algorithm for Detecting the Colour coded boxes and control of 3 DoF robotic manipulator*

The overhead camera which monitors the load pickup area of the warehouse continuously searches for any colour coded boxes in that area. Multi-threading functionality of Python is

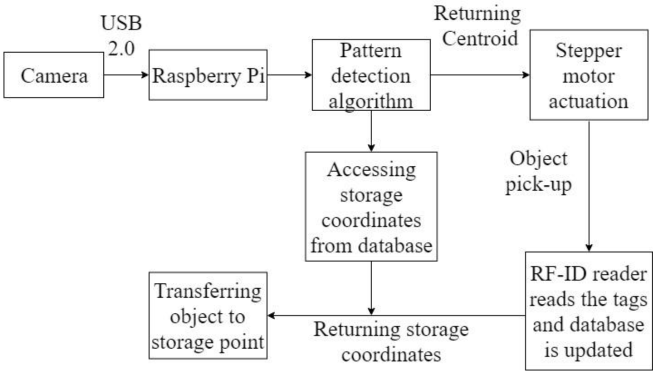

Fig. 8. System process overview.

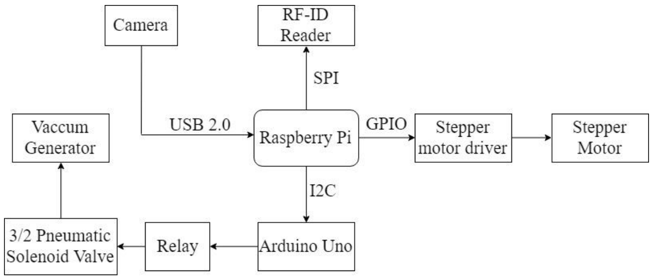

Fig. 9. Hardware communication and control.

used for capturing images from the live video stream and processing them side-by-side. The former thread will continuously capture images from the video feed while the latter thread access these captured images and process them to identify the centroid of objects in the unloading zone. The end effector is found to efficiently pick up a load if the pneumatic suction cups align with the centroid of the box .In order to detect the centroid of the colour coded box, at first, RGB ground truth images are obtained from the camera feed. Since the camera use wide angle lens, the frames are subjected to barrel distortion. For locating the objects accurately in the frames, an undistortion operation is performed based on evaluating some intrinsic camera parameters and distortion co-efficients. These parameters are shown below:

$$\text{Camera Matrix} = \begin{bmatrix} 971.6973 & 0 & 283.8859 \\ 0 & 977.3484 & 293.67 \\ 0 & 0 & 1 \end{bmatrix}$$

$$\text{Radial Distortion} = \begin{bmatrix} -0.1148 & -0.2157 & 1.0123 \end{bmatrix}$$

$$\text{Tangential Distortion} = \begin{bmatrix} 0.00032 & -0.0024 \end{bmatrix}$$

The undistorted images are then converted to Hue, Saturation and value (HSV) image. Masks for identifying different colours are developed which on bitwise AND operation with the HSV image will identify different colour patterns. Contours of the identified patterns are used to locate the centroid of the object in order to move the end-effector towards it for picking it up. The boxes from the perspective of the camera frame is shown in Fig. 10.

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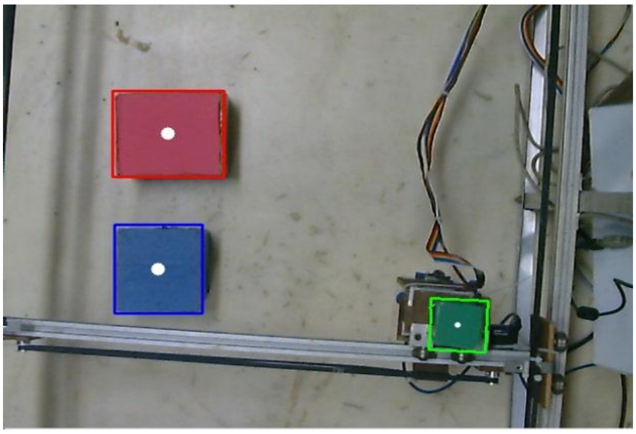

Fig. 10. Detection of colour coded boxes

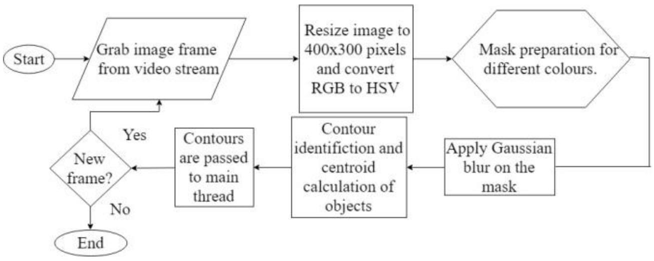

Fig. 11. Algorithm for localising the boxes

The green colour on the end effector serves as a marker for the camera to identify the position of end effector in the workspace. The real world dimensions and pixel dimensions of the model is used to establish a relationship between distances travelled in real world and in camera frame. The algorithm for extracting colour coded boxes from the camera frame is outlined in Fig. 11. A 1 cm distance travelled by the load in real world is equivalent to 10 pixels in camera frame. Raspberry Pi controls the three stepper motors for coordinating the movement of end-effector on which the picking mechanism and RF-ID reader are mounted. The real world distance to pixel scaling factor is used by the Raspberry Pi to determine the end effector pose to pick up the load. Two of the stepper motors handles motion in the x-y plane and move the endeffector using a belt and pulley mechanism to a point above the centroid of the object. With the help of a lead-screw, third stepper motor moves the end-effector towards the object. Once the suction cups are aligned with the box the 3/2 pneumatic valve is actuated through an Arduino microcontroller and a relay mechanism thereby generating suction and grabbing the object.

B. *Smart Inventory management using IoT*

RF-ID reader attached to the picking mechanism reads the tag on the object and updates the Warehouse inventory database hosted on the Raspberry Pi through SPI communication. Fig.12 shows the web page maintained for updating and viewing a MySQL database which keeps track of the stock in the warehouse. An operation called scheduling is done for defining the storage location of the stock in the warehouse. Scheduling operation involves obtaining the colour code and target coordinates of the load. The above entries are used to create a slot in the database for storing the object details. Contents of the database can be viewed in a tabular format from the web page.

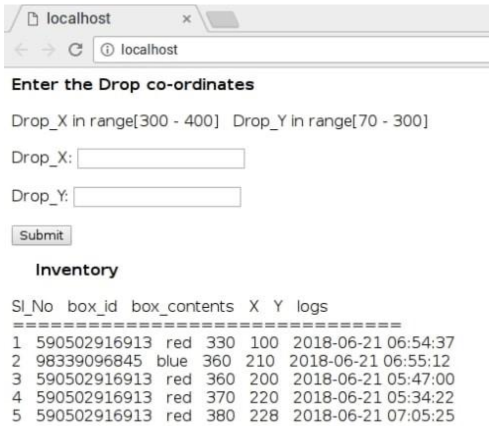

Fig. 12. Webpage for scheduling operations.

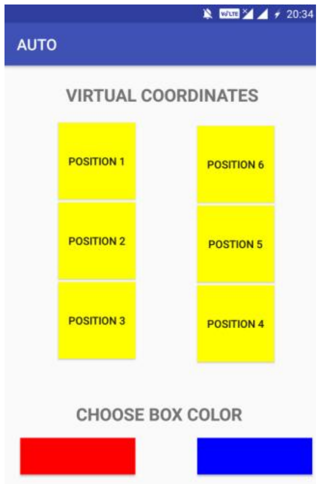

Fig. 13. UI of smartphone application.

Since smartphones are ubiquitous, an Android application was created using which an operator can schedule the movement of colour-coded boxes to target locations at the storage area. Fig. 13 shows the user interface of the Android application developed for the AWMHS. The X and Y co-ordinates of the storage location can be entered from the User Interface (UI) of the app and the values are transmitted as JavaScript Object Notation (JSON) name/value pairs over Wi-Fi to the database as illustrated in Fig. 14. The contents of the boxes are updated in the database after the RF-ID reader reads the tag on each box. A timestamp is also entered to mark the time of arrival of the box at the warehouse.

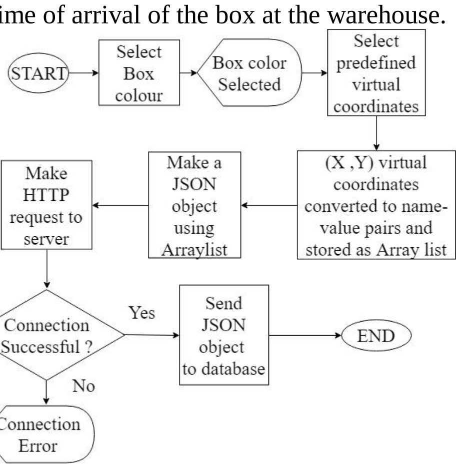

Fig. 14. Working of smartphone application

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IV. RESULTS AND DISCUSSIONS

A. *Design and Fabrication of AWMHS*

The scaled down prototype model was made out of extruded aluminium channels to test the AWMHS as shown in Fig. 15. The model was constructed with dimensions 100cm × 60cm. NEMA 17 Stepper motors satisfying the necessary torque requirements of the model were chosen as the actuators driving a belt and pulley mechanism for motion in the x-y plane and a lead screw mechanism for movement in the z plane. The warehouse floor was divided into two zones- a loading area and a storage zone. A single USB camera was mounted parallel to the floor of the warehouse such that the loading zone was in its field of view.

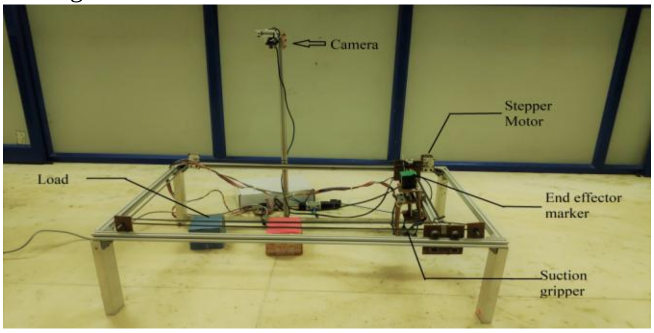

Fig. 15. Scaled model of AWHMS

B. *Actuator Selection*

The torque requirements for the belt drive and lead screw mechanisms were determined from dynamic modelling of the system. Assuming a safety factor of 1.5, the maximum torque requirements of the three motors were calculated as 0.134kgcm, 0.096kgcm and 0.873kgcm respectively. Therefore, NEMA 17 Steppers motors with 5.5kgcm torque were used as the actuators in the prototype model.

C. *End-effector Design*

The end effector consists of an adjustable platform moved with the help of a lead-screw driven by a stepper motor. Suction cups are attached to this platform, which is actuated with the help of a 3/2 pneumatic valve. The compressed air from the compressor is passed through a vacuum suction nozzle to generate the suction necessary to lift the load. An RF-ID reader is also attached to this adjustable platform for reading the RF-ID tags on the boxes. The RF-ID reader is positioned such that the RF-ID tags on the boxes are read when the boxes are lifted while being transported to the storage area. The pneumatic circuit diagram is given below in Fig.16.

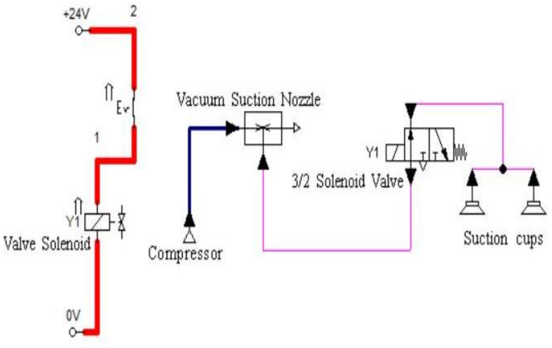

Fig. 16. Pneumatics circuit diagram for suction gripper.

D. *Experimentation*

An experiment was designed to verify the accuracy of the AWMHS in detecting a load in the load pickup area and transporting it to the desired location. The experimental study was conducted using a payload of 700g in a blue coloured box. The box was equipped with an RF-ID tag and was placed in the load pick-up area. The box in the pick-up area is equivalent to a load arriving at a warehouse. The camera mounted overhead was used to map the warehouse floor into a 400 × 300 pixels rectangle. The green coloured marker on the end effector was used to track its position in real time. The initial position of the end effector served as the origin for the coordinate system covering the warehouse floor. The desired location to which the load was to be transported was entered into the database using the web page. The final position is the x and y coordinates of the point to which the box was transported by AWMHS. The desired and final position are in terms of pixels as observed from the camera. The performance of AWMHS in transporting the load accurately to the desired location was analyzed by calculating the variation between the desired and final coordinates of the box. The results and observations from multiple trials are tabulated in Table. III.

Table III: Performance analysis of AWMHS

SI. No	Desired position (pixels)		Final position (pixels)		Variation (%)	
	x	y	x	y	x	y
1	330	100	323	106	2.12	6
2	360	210	354	204	1.67	2.86
3	360	200	365	200	1.39	0
4	370	220	361	215	2.43	2.27
5	380	228	371	233	2.37	2.19
Average variation					1.99	2.66

The variation in the x and y directions is observed to be 1.99% and 2.66% respectively. The AWMHS can automate operations in a warehouse and reduce the human intervention to a minimum.

The smartphone application along with the web page make it easy for the operators to manage the material handling operations in a warehouse. The inventory management feature of AWMHS implemented using RF- ID tags and IoT technology ushers warehouses to the age of Industry 4.0.

V. CONCLUSION AND OUTLOOK

The AWMHS can perform material handling operations and inventory management of an entire warehouse with minimum human intervention. The AWMHS can replace the existing technologies used for automating processes in a warehouse such as AGVs and offers a single, centralized solution for material handling and inventory management. AWMHS combines image processing, RF-ID technology and IoT which makes automating warehouses possible. The accuracy and precision of the AWMHS in transporting payload in a warehouse is experimentally verified.

The system can further be improved in few aspects. Wide angle cameras can increase the field of view but will require image transformations to compensate for the distortion. Another solution to this problem involves the use of multiple cameras to monitor the warehouse. Machine learning algorithms can be employed for further optimizing the end effector path panning. The present AWMHS mechanism can be made versatile by making it mobile. This type of configuration can be used in shipping ports for efficient material handling.

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Dr. Sudheer. A. P is currently an Assistant Professor, Mechanical Engineering, National Institute of Technology Calicut (NITC). He is in teaching, research and academic administration for the last 20 years. He has nearly 30 publications in International and national journals and conferences. He is guiding MTech and PhDs students. He has filed for four patents in the area of robotics. His research interests are kinematics, dynamics and control of robotics, mobile robotics and vision systems. He is a member of "the Robotics Society-India"(TRS-India) and ISTE. Presently he is the editor of TRS-India.

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