Design of Automatic Charging System for Electric Vehicles using Rigid-Flexible Manipulator

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***Abstract*—Last few years have seen a remarkable growth in the number of Electric Vehicle (EV) users. Autonomous driving and parking of EVs are the future of vehicle industry and this calls for customer friendly and innovative charging infrastructure development. A fully autonomous charging system highly aid them. This paper proposes the design of an automatic charging system for EVs. In this work YOLO (You Only Look Once) algorithm, a deep neural network based object detection algorithm is used to automatically recognize and locate the charging port of an EV. Thus accurate positioning of charging port in a complex environment can be achieved. A rigid - flexible manipulator on a movable platform is then designed for conductive charging of an EV automatically. Irrespective of vehicle models and charging ports the proposed design can be used for the automatic charging of EVs. The designed robotic manipulator successfully follows the path traced by the charging port detection system and perform plug-in process. The simulation results show the efficacy of the proposed design.**

***Index Terms*—Electric Vehicle; Automatic Charging; Rigid-Flexible Link Manipulator**

I. Introduction

Currently for reducing greenhouse gas emissions EVs provide a promising solution by relieving the usage of fossil-based fuels [1]. A remarkable growth in charging infrastructure has been witnessed in the last decade, resulting in a high demand of electrified vehicles [2]. The accessibility to convenient and fast battery charging facility, especially while traveling longer distances is still a difficult task for EV users. If the charging plug is connected to an EV manually then there is a chance that the charging device remain connected to that EV even if it is fully charged, until someone unplug it manually [3]. Automated charging system can be employed to solve this problem.

The future of vehicle industry lies in autonomous driving and parking system. A fully autonomous charging system tremendously help them. The unification of an autonomous parking and recharging system in a charging station definitely benefit the EV users [4]. The automatic charging system helps in sharing of charging piles when the charging demand is huge. Thus provide a solution for insufficient supply of charging piles. This brings better experience to EV users at the same time lower the severe impact on the power grid resulting from uncontrolled charging.

Both at academic and industrial level, many research works had been done in automated charging solutions. Volkswagen of Germany has introduced the E-smart Connect system [5]. In their design the vehicle is automatically charged by a KUKA LBR iiwa robot. The vehicle's charging socket has to be placed in 20 by 20 centimetres target area. Thereafter the camera affixed on the robot detects the charging socket's position, accurately defined to a millimetre. But this is applicable only to a particular vehicle model with a specific charging port type.

An auto-charging system prototype called ALanE is proposed by the Dortmund Technical University. Their design is based on smart phone controlled robotic arm suited to automatically plug-in and unplug the charging plug [6]. PowerHydrant's computer-vision robot will automatically align to the vehicle charging port and it can handle all charging levels including DC fast charging [7]. Designs build on articulated manipulators are efficient in plug-in and unplugging the charging connectors of EVs automatically. Nonetheless the technical details of the adaptability for various types of charging ports, rectification of positioning error of charging ports etc. are not addressed in these works.

Automatic charging systems are also designed using Automated Guided Vehicles (AGV). Samsung's robotic charging unit named Electric Vehicle Automatic Recharging device (EVAR) uses AGV [8]. If an EV is required to be charged, the driver of the vehicle has to use his smartphone and tag it to a wall-mounted device. EVAR can automatically locate the vehicle and it move towards the vehicle and connect to charge on its own. However, in this design EV users have to attach an adapter to the number plate which is used for the identification of vehicle. Bionic manipulators are also used for automatic charging [9]. Tesla charging-robot based on bionic snake-like robot arm can identify parked vehicle charging socket. When the robot and the vehicle charging port are connected, the charging begins autonomously. The detailed technical information and actuation method are not available in literature yet.

Based on the mechanical structure, the available automatic charging robots are mainly classified into two types which are traditional articulated industrial robots and flexible bionic manipulators [10]. The former has the advantage of simple and mature modelling, but the end-effector's dexterity of such robot is limited. This makes the plug-in and unplugging task harder especially while working in confined spaces with any obstacles. On the other hand flexible robotic arms has the advantage of improved dexterous operation, when used

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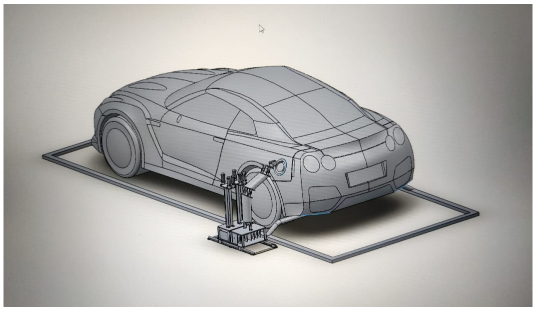

Figure 1. Model of automatic charging robot

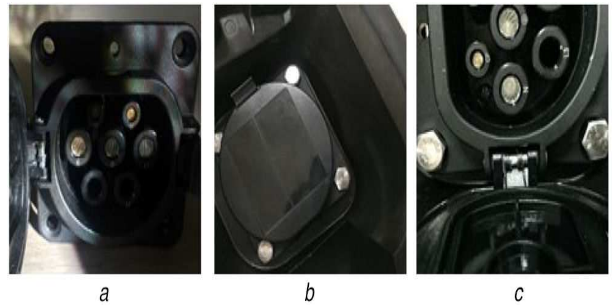

Figure 2. Complex environment in charging port detection (a) Uneven illumination level (b) The charging socket protector cover is not opened (c) Partial missing image [18]

for EV charging. This property provides better flexibility to the charging plug and also helps in obstacle avoidance. But the stiffness of these type of charging robots are poor and hence proper vibration control is required inorder to achieve high position accuracy [11]. This paper presents an automatic charging robot for charging EVs based on rigid – flexible manipulator. The modelling and control [12], [13], [14] for rigid- flexible manipulators for different applications are available in literature. To the author's knowledge, little research on rigid – flexible manipulator based auto charging robot has been performed.

The location and type of charging ports are not unique. It varies with vehicle model and a common standard is not established by the car manufacturing companies yet [15]. The accurate detection of charging port location plays a key role in the success of automatic charging systems. Researchers have developed many methods for this. In [16] a method using a Radio Frequency Identification (RFID) tag, which is installed in the vehicle is used. Using these tags, identification and location of charging port can be easily performed. But this method calls for modification of vehicles and not suitable for non-adapted vehicles.

The most commonly adopted method to identify charging port location is using machine vision systems [17]. These systems mostly use a camera to get two-dimensional images and computer vision algorithms to process these images. Thus they can accurately determine the 3 dimensional details of the object.

In this work, we present a 4-DOF rigid- flexible manipulator based automatic charging system. A two link rigid- flexible manipulator which is placed on a movable platform is designed. The exact location of the charging port is obtained by combining machine vision and YOLO CNN (Convolutional Neural Network). YOLO stands for You-Only-Look-Once. The plug-in and unplugging process are designed in such a way as to respond to various parking situations. The schematic of a typical automatic charging robot is shown in Fig.1.

The remaining sections of this paper are arranged as follows. Section II describes the vehicle charging port detection system. Section III explains the automatic charging system. In section IV simulation results are brought in. Section V poses the conclusions and future works of the proposed research.

II. CHARGING PORT DETECTION SYSTEM

The location and type of charging ports varies with vehicle model so an accurate charging port detection system plays a crucial part in the success of automatic charging system. The most commonly used method is using machine vision. Texture-less black plastic material is commonly used for making vehicle charging ports, so it is very difficult to obtain good features in camera images. In addition to that uneven illumination, partial missing etc. affect the exact location identification process[18]. These are shown in Fig. 2. The charging port structural details can cause interference in images. The difference in height between the edge of the hole and metal core may cause obstruction during imaging. While processing of the images, the complex structure of the charging port may sometimes cause the match-based image processing methods to fail. The accurate segmentation of charging port images are a difficult task considering the complex internal structure of many available charging ports. This causes errors while feature detection. A suitable charging port feature selection is essential to avoid the difficulties caused by the aforementioned complex environments.

In this work the exact location of charging port in complex environment is obtained by using machine vision system and YOLO CNN algorithm. CNN is a class of deep neural network mostly designed for processing structured array of data like images. CNN has many convolutional layers stacked on top of each other. Each one of these layers are capable of recognizing more sophisticated shapes.

The first step in identification of charging port is construction of sample set which includes the images of charging port considering the complex environment. The sample set of charging port images are categorized into three sets as shown in Fig.2. Each set consist of 2000 images. The noises in these images are suppressed using median filter algorithm. First training and test is done with some images of charging port and it is classified depending on the intensity of light as strong, medium and weak. After that second set of training and test is conducted for light intensity information. If control over the camera position and light intensity are required for getting better images, then the output can be fedback to the automatic charging system.

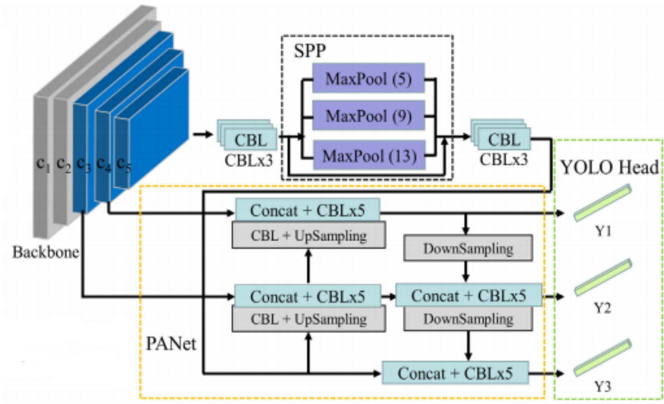

Figure 3. Overall structure of YOLOv4 [19]

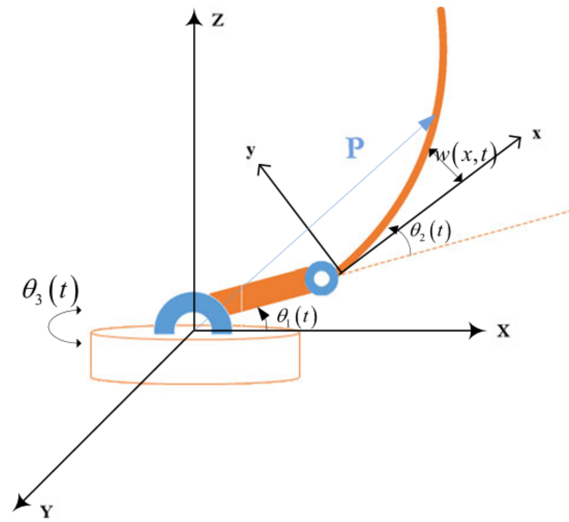

Figure 4. Model of rigid – flexible manipulator [21]

The object recognition model used is YOLOv4[19]. It frames object detection as a regression problem. It is fast by design while keeping good accuracy. Its structure is shown in Fig. 3. It can be trained directly on full images and is simple to construct. It guarantees fast and robust object detection. The model structure of YOLOv4 consist of CSPDarknet-53, Spatial Pyramid Pooling additional module (SPPnet), Path Aggregation Network (PANet) and three YOLO heads. CSPDarknet-53 act as the backbone that augments the learning capacity of CNN and it is responsible for extracting deep features of the input images. The SPPnet is attached overhead CSPDarknet-53 for improving the receptive field and distinguish highy important context features. The network contains 53 convolution layers with the sizes of 1×1 and 3×3, and each convolution layer is connected with a batch normalization (BN) layer and a Mish activation layer.

III. Design of automatic charging system

Upon receiving the exact location of charging port of the vehicle to be charged, the robotic arm completes the connection and starts conductive charging. The robotic arm is constituted with two link rigid-flexible manipulator and three joints. The end effector of the robotic arm is the charging plug which is flexible. The rotational elastic deformation acting on the charging plug around 3 mutually perpendicular axis, during plug-in process can be reduced by the flexibility provided at the end effector. The robotic arm is designed in such a way that all the links are hollow, thus charging cables are routed along the inside of these links. The robotic arm is placed on a movable platform. The robotic arm equips two translational motion along the up-down and left-right directions of vehicle. It also allows one rotational motion about the front and back direction of vehicle. The movable platform administers the translational motion along the front and back direction of vehicle. At the same time, the flexible plug gives small rotational motion about three mutually perpendicular axes. Thus, the movable platform, the robotic arm and the flexible plug altogether could complete plug- in and unplugging task.

A. The dynamic model of manipulator

The dynamic model of two-link rigid-flexible manipulator system is outlined here which is shown in Fig. 4. Let $\theta_1(t)$ be the angular position of rigid link, $w(x,t)$ be the deformation of the flexible link and $\theta_2(t)$ its joint angle. The angular position of rotatable base is $\theta_3(t)$ which is measured counterclockwise from x-axis. Euler-Bernoulli beam theory [20] based model of flexible-link robots is considered here. Let the length of the rigid link be L_1 and L_2 that of the flexible link. J is the moment of inertia of rotatable base; J_1 that of rigid link and the moment of inertia of flexible link is J_2; the mass of joint is given by m; and ρ the mass density per unit of flexible link and EI be the Uniform flexural rigidity.

The position vector P is introduced to describe the manipulator in the global coordinate system.

$$P_x = L_1 \cos\theta_1 \cos\theta_3 + x\cos(\theta_1+\theta_2)\cos\theta_3 \\ -w(x,t)\sin(\theta_1+\theta_2)\cos\theta_3 \tag{1}$$

$$P_y = L_1 \cos\theta_1 \sin\theta_3 + x\cos(\theta_1+\theta_2)\sin\theta_3 \\ -w(x,t)\sin(\theta_1+\theta_2)\sin\theta_3 \tag{2}$$

$$P_z = L_1 \sin\theta_1 + x\sin(\theta_1+\theta_2) \\ + w(x,t)\cos(\theta_1+\theta_2) \tag{3}$$

The kinetic energy E_k of the system is given by

$$E_k = \frac{1}{2}J_1\dot{\theta}_1^2 + \frac{1}{2}J_2\left(\dot{\theta}_1+\dot{\theta}_2\right)^2 + \frac{1}{2}J\dot{\theta}_3^2 + \\ \frac{1}{2}mL_1^2\theta_1^2 + \frac{1}{2}\rho\int_0^{L_2}\dot{P}^{\mathrm{T}}\dot{P}dx \tag{4}$$

There is deflection of the flexible link and the position energy E_p, due to this is given by the following equation.

$$E_p = \frac{EI}{2}\int_0^{L_2}\left[w_{xx}(x,t)\right]^2 dx \tag{5}$$

Hamilton's principle [21]is applied to derive the dynamic model, which allows the derivation of energy quantities in a variational form. It follows the property of the Euler-Bernoulli beam for very small displacement. The principle states that the sum of variation of the kinetic and potential energy and the variation of work done during any time interval must be equal to zero, which is given by,

$$\int_{t_1}^{t_2} (\delta E_k - \delta E_p + \delta W)\, dt = 0 \tag{6}$$

Here δ is the variation, t_1 and t_2 are two time constants and δW is the variation in the virtual work done by the three actuators which is given by the following equation

$$\delta W = \tau_1 \delta\theta_1 + \tau_2 \delta\theta_2 + \tau_3 \delta\theta_3 \tag{7}$$

where τ_1, τ_2 and τ_3 are the three actuator torques of the rigid link, the flexible link and the movable base respectively.

Vibrations arises due to the elastic deformation of flexible link. For achieving better trajectory tracking control of manipulator endpoints simultaneous control of trajectory and vibration is necessary [22].In order to compensate the actuator faults that may encounter in the three actuators of FLM, Adaptive Fault-tolerant control (FTC) laws are designed. Actuator faults are modeled as

$$\tau_{ri} = \beta_i \tau_i (i = 1, 2, 3) \tag{8}$$

where τ_{ri} and τ_i are the actual outputs and given output of three torque actuators, respectively.The degree of actuator failure is represented by β_i. Its value varies from 0 to 1. If $\beta_i = 0$ that means complete failure and if $\beta_i = 1$ then no actuator failure.

The control objectives are that the joint angles will be achieved at the desired angles at the final state and the deflection and vibration are eliminated.The defined $\theta_{id}(i = 1, 2, 3)$ are the desired angles of the rigid link, flexible link, and movable base respectively. Then the main control objective is to achieve the desired angle at each joints.

$$\theta_i \to \theta_{id} \tag{9}$$

$$w(x, t) \to 0, \dot{w}(x, t) \to 0 \tag{10}$$

The Adaptive FTC laws are defined as follows

$$\tau_1 = -K_{1p}e_1 - K_{1d}\dot{e}_1 - k_1\hat{p}_1\dot{e}_1 \tag{11}$$

$$\tau_2 = -K_{2p}e_2 - K_{2d}\dot{e}_2 - k_2\hat{p}_2\dot{e}_2 \tag{12}$$

$$\tau_3 = -K_{3p}e_3 - K_{3d}\dot{e}_3 - k_3\hat{p}_3\dot{e}_3 \tag{13}$$

where K_{ip}, K_{id} and $k_i, i(i = 1, 2, 3)$ are positive constants. $p_i = \frac{1}{\beta_i}(i = 1, 2, 3)$ and $\hat{p}_i(i = 1, 2, 3)$ is the estimate of p_i and the error $e_i = \theta_i - \theta_{id}$

The adaptation laws for actuator failures are modeled as follows

$$\dot{\hat{p}}_1 = k_1\gamma_1\dot{e}_1^2 \tag{14}$$

$$\dot{\hat{p}}_2 = k_2\gamma_2\dot{e}_2^2 \tag{15}$$

$$\dot{\hat{p}}_3 = k_3\gamma_3\dot{e}_3^2 \tag{16}$$

where $\gamma_i, (i = 1, 2, 3)$ are positive constants.

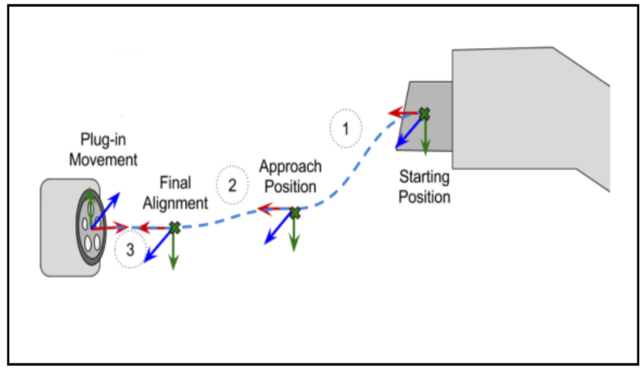

Figure 5. Plug-in procedure

B. Plug-in and Unplugging Strategy

Plug-in and unplugging of charging port can be optimized so as to include possible parking errors. The flexible plug can reduce the requirement for position accuracy. In addition to that the flexible end link has better flexibility. The main task in the plug-in process is to coordinate charging plug and the vehicle charging port such that the final movement of charging plug is along a single axis only. Since the movable platform provide translational motion along the length of the vehicle, the workspace of end effector is a rectangular plane for plug-in action. The width of this workspace is the distance between farthest and closest point that plug can reach and the length is given by the moving range of the platform and this plane is at a height of the location of charging port from ground.

After the exact location of the vehicle charging port is identified, the coordinate system is assigned with Z-axis looking outwards and the origin fixed at the middle of the charging plug. The flexible plug which the robot hold, is also assigned with the coordinate system. The robotic arm then moves the plug to the 'plug-in position' at comparatively high speed, after considering the position of the charging port. It will stop within a 10 cm radius from the charging port. Then the robotic arm will reduce the speed to 10 percentage of the maximum allowable robot joint speed. The arm will then reach the final alignment position in which the flexible plug and the vehicle charging port are fully aligned. At this position both the plug and the charging port are only a few millimeters away from their contact point. Finally the flexible plug move slowly along Z-axis and complete the plug-in process. The torques and forces exerted by the flexible plug on to the vehicle charging port must be continuously monitored otherwise it may damage the charging plug or port. The robot must stop at once these forces are exceeding a given threshold value. Fig. 5, shows the plug-in procedure. The elastic deformation of flexible plug will increase as the insertion depth increases, during the plug-in motion. After plug–in procedure is completed, the robotic arm remains stationary for some time to start the charging process.

When the connected vehicle is charged upto its desired battery level or to its full capacity, the robotic arm is dis-

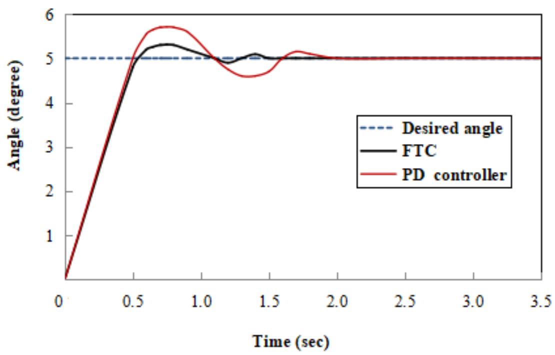

Figure 6. Joint angle tracking

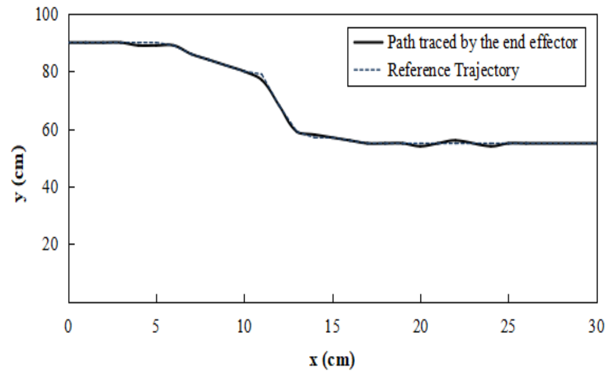

Figure 7. Path traced by the end effector

connected. The battery level is continuously monitored using suitable circuitry. The unplugging process starts as soon as the charging process is completed and it is assumed that there were no change in position during the entire charging process. The unplugging path simply follow the recorded way points of the plug-in procedure in the reverse order. The robot returns to the original approach position and remain at its stand-by position.

Table I
PARAMETERS OF MANIPULATOR

Parameter	Numerical Value	Parameter	Numerical Value
L_1	$0.6m$	J	$0.02kgm^2$
L_2	$0.8m$	m	$2\ kg$
J_1	$0.15kgm^2$	ρ	$0.52kg/m$
J_2	$0.02kgm^2$	EI	$5Nm^2$

IV. RESULTS AND DISCUSSION

Based on the information of charging port location from the charging port detection system, the motion between pre-plug-in position and plug-in complete position is planned. The tracking performance is simulated using MATLAB simulation platform. The parameters used for simulation are given in Table 1.

Table II
PARAMETERS OF CONTROLLER

Parameter	Numerical Value	Parameter	Numerical Value
K_{1p}	10	K_{2d}	2
K_{2p}	5	K_{3d}	1
K_{3p}	3	k_1	10
K_{1d}	3	k_2	12
k_3	5	γ_1	2
γ_2	1	γ_3	2

Inorder to demonstrate the effectiveness of FTC on manipulator performance, joint angle tracking is verified by setting desired angle as a constant. The result is compared with a PD (Proportional Derivative) controller. The β_1 value is set as 0.2, β_2 as 0.15 and β_3 as 0.25. The controller parameters are given in table 2. The joint 1 angle tracking is shown in Fig. 6. The simulation results demonstrates the better performance of the FTC over PD controller for actuators faults.

The simulation result in Fig.7, shows the tracking performance of the end effector. The dotted line is the desired trajectory that is also the required motion trajectory of the end effector for plug–in action. The solid line is the practical motion trajectory of end effector. Good tracking performance is observed using the designed controller. The control accuracy directly reflect the effectiveness of vibration control of rigid-flexible manipulator used in the automatic charging system.

V. CONCLUSIONS

In this paper, an automatic charging system for electric vehicles is designed. Charging port detection system based on machine vision and YOLO algorithm can accurately locate the exact position of vehicle charging port. An automatic charging system for conductive charging of EV using rigid-flexible manipulator on a movable platform is designed. The proposed system can be used for automatic charging of any EV model. From the simulation results we can infer that the designed robotic manipulator successfully follows the path traced by the charging port detection system. In future experimental validation of the designed automatic charging system will be performed.

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