Mechatronic Design and Development of an Autonomous Mobile Robotics System for Road Mark Painting

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Abstract— this paper presents a mechatronic design and development of a new WMR experimental rig prototype for autonomous road marks painting. The platform includes three main units: differential drive unit, measurement and vision unit and processing unit. The sensors, actuators and the interface free controller cards are connected together in such a way that ensures high performance for exchange the data from the on-board computer to the sensors and actuators. The embedded controller of the proposed platform has been developed to integrate the mechanical components with electronics and software algorithms. The painting system is attached on the WMR platform to perform autonomous on-the-road mark painting. The design, components, control of the paint task and the connection to the main WMR controller are also presented.

Key-words:— Autonomous, Navigation, Wheeled Robotics System , Road Marks, Painting System.

1 Introduction

Several Mobile Robotics platforms have been developed in last few years to launch with certain tasks that represent as hazard, dangerous and heavy to be performed with people interaction. Thus researchers try to substitute most of the systems that need human to operate such above-mentioned systems either those which are working manually or adjusted automatically by autonomous systems that are intelligent enough to do the tasks without any human interactions.

SCARF vehicle for detection the road regions is proposed by [1] using extracting of colour information method. In which, the system can recognize even the roads with faded surfaces, edges without lane markings and Y intersections without pre-predictions from the navigation system. This work is considered as the first system for online intersection detection. SCARF navigation includes two functions: detection of road surface and interpretation generation. The detection of road-surface estimates from the input image the location of the road and it provides so called road-surface likelihood image using Bayesian networks and pattern recognition where every pixel in this image contains the probability belongs to the road surface. The interpretation generation function matches a set of road and intersections to the road-surface likelihood image using match-filter technique.

Driver assistance system (ROMA) for detecting the lane of roads and road intersections is proposed by [2]. This system uses the sequence of images for the signs of roads to detect the lane of roads and road intersection. It depends on the two approaches to localize vehicle in road: Contour-based methods, which are used for road border detection and depends on calculation of a gradient direction of image in real time. The second approach is a segmentation of road to find dashed and solid marking lines for intersection detection.

Laser based navigation system has been used for navigating vehicles over the roads in difficult situation (either at night or day) [3]. The system can track and extract the borders of the road in non-cooperative situation like no printed signs on road, driving in the night, etc..This system uses two algorithms: the first one is so called detection algorithm which is aimed to extract the road edges from the range data using statistical approaches and distinguish those data into two parts road surface or edge/side-zone of roads. The second one is the estimation model which is used for continuous

$$F_w = F_{w1} = F_{w2} = F_{w3} = \frac{F_g}{3} + F_{gw}$$	(4.2)

tracking of the road borders. It uses discrete Kalman filter to estimate the state vectors and updating measurements.

A navigation system for trajectory tracking, obstacle avoiding and localization in curbed roads is proposed by [4]. In this system, the tele-operation and autonomous navigation are performed in the curbed road environment through a combination between DGPS and odometry with extended Kalman filter, which is used to localize the mobile robot within road environment; however the LRF is used for avoiding the obstacles when they occurred by finding the suitable path to pass within the roads curbs. Also LRF is used to estimate the position of the road curbs during trajectory tracking.

A new autonomous mobile robot platform will be developed in this paper to perform autonomously the road marks painting which is accomplished in almost existed systems over the world with manual devices.

2. Platform Design

The platform is driven by two differential drive wheels (actuated by motors) and a castor wheel as in Fig.1.

The forces that act on the wheels can be calculated from the equilibrium of active and reactive forces as follows:

$$\sum F_w = F_g + 3F_{gw} \qquad (1)$$

F_w is reactive force acting on the wheels, F_g is the total weight of the robot. F_{gw} is the weight of the wheels.

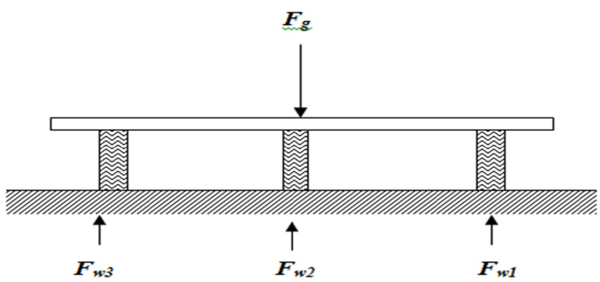

Fig.1 A free body diagram of the robot

If the distances between the robot center gravity and wheels are similar, the force on each wheel can be calculated as follows:

When choosing the wheels motors, many parameters should be taken into consideration to determine the maximum torque required. These parameters were selected as follows:

- Total mass of robot (m_r) without wheel: 200 kg
- Wheel mass (m_w): 3 kg
- Radius of wheel (r): 10.5 cm
- Maximum acceleration (a_{max}): 0.5 m/s^2
- Maximum incline angle (inc): 3 degree
- Working surface: can be chosen from Table 4.1

The required traction force to move the robot can be computed as follows:

F_{tot} is the total traction force needed to move robot for maximum acceleration (a_{max}). F_{rr} is the force needed to overcome the rolling resistance. F_{sr} is the force required to overcome the slope resistence. F_{ac} is the force required to accelerate the robot.

$$F_{tot} = F_{rr} + F_{sr} + F_{ac} \qquad (4.2)$$

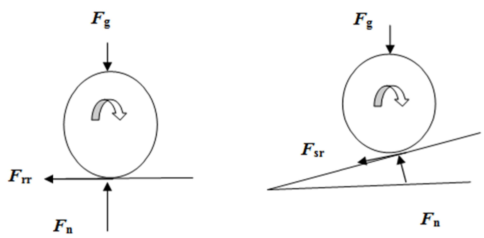

Fig. 2 Free body diagram of the robot's wheel

F_{rr} can be calculated as a function of the normal force acting on the wheel as shown in Figure 4.2. The reactive normal force can be computed as follows:

The total mass of robot and wheel (for one wheel):

$$m = m_w + \frac{m_r}{3}$$

The surface coefficient of friction is chosen from

$$F_n = F_w = mg \qquad (3)$$

Table 4.1, C_{rr} = 0.012 (good asphalt), and F_{rr}=23.8 N

$$F_{rr} = F_n c_{rr} = mg\ c_{rr} \qquad (4)$$

Table 1: Surface coefficient of friction [5]

Contact Surface	C_{rr}
Concrete (good / fair / poor)	.010 / .015 /.020
Asphalt (good / fair / poor)	.012 / .017 / .022
Macadam (good/fair/poor)	.015 / .022 / .037
Snow (2 inch / 4 inch)	.025 / .037
Dirt (smooth / sandy)	.025 / .037
Mud (firm / medium / soft)	.037 / .090 / .150
Grass (firm / soft)	.055 / .075
Sand (firm / soft / dune)	.060 / .150 / .300

The slope resistance force is shown in Fig. 2 and can be calculated as follows:

$$F_{sr} = mg\sin(inc) = 104.1\ \text{N} \quad (5)$$

The acceleration force can be computed as follows:

$$F_{sr} = ma_{max} \quad ; \quad F_{sr} = 101.5\ \text{N} \quad (4.5)$$

The total traction force is $F_{tot} = 229.4$ N

The total torque needed to accomplish the robot movement can be calculated as follows:

$$\tau_{req} = F_{tot}\, r\, \tau_f$$

τ_f is the torque factor that represents the frictional losses between the wheels and their axles and the drag on the motor bearings. It is located with the range (1.1 - 1.5) Nm. In the worst case, $\tau_f = 1.5$ Nm and the required torque is thus $\tau_{req} = 36.13$ Nm. The torque of the motor can be calculated from the required torque acted on the wheel with knowing the gearbox ratio as follows:

$$\frac{\tau_{req}}{\tau_{mot}} = \frac{n_{mot}}{n_{req}} = \mu$$

μ is the gearbox ratio, n_{mot} and n_{req} are the rotation speeds of the motor and wheel, respectively. If the rotation speed of DC motors is 3000 rpm and the output rotation speed is 100 rpm, then the torque of the motor is $\tau_{mot} = 1.2$ Nm.

Two DKM brush motors with torque equalling 6.3 Nm are chosen to drive the robot. This motor is equipped with a gearbox that has a gear ratio of 1:30. The length of each motor and its gearbox is 24cm which makes the length of the robot shaft 50 cm and the total width of the robot 80 cm. The length of robot is chosen to be 100 cm to enable robot for loading objects with large dimensions such as airless painting pump. The height of LRF and camera supporting holders are chosen to be 80cm and 65cm, respectively, to enable for good viewing of the environments. The others holder's dimensions on the robot platform are chosen adequately to hold the other robot components such as batteries, encoders, IFC electronic cards and airless painting pump as shown in Fig.3, 4 and 6.

3. Platform Components

The platform includes three main units, namely, the differential drive unit, measurement and vision unit and processing unit.

3.1 Measurement and Vision Unit

The measurement and vision unit includes the sensors that are used to measure the movement of the robot and localize it within environments.

LRF (*HOKUYO URG-04LX-UG0*)1 is one of the most suitable for area scanning. The light source of the sensor is infrared laser of wavelength 785nm with laser class 1 safety. The scan area is 240º semi-circle with maximum radius, 5600 mm and resolution 0.36º. The scan time is 100 ms/scan and LRF measures 683 points per each scan with accuracy ±30mm. It is used to find the path of the robot during navigation (for curbed roads).

A wifi camera (*JVC GC-XA1B*) produces a live streaming video for the surrounding environments and is used to extract the features of the road that will be used later for path decision and finding. Image sensor is 5 mega pixel (MP) CMOS sensor with four operation modes: video record, photo record, live streaming via WiFi, wireless webcam. The lens is fixed focus with *focal length* equal to 2.8 and with a range from 50 cm to infinity.

Odometry measurement is accomplished using two rotary encoders (*B106*) to estimate the angular positions of the robot wheels. Rotary encoder is used to calculate the angular rotation of the shaft. Depending on the pulse per rotation, user may encode the position by counting the accumulative pulse.

3.2 Processing Unit

The processing unit contains the following parts:

A motor driver (*SmartDrive 40*) that will supply the current to the motor and protect the motors from starting current load until 80 A, overheating, etc. *SmartDrive40* can also be hooked up with another similar unit and operates in pair which make the driving of a robot with differential drive easy.

The Interface Free Controller Cards (*IFC*) is used to exchange the sensing and actuating data between the main controller and the sensors or actuators. There are several kinds of IFC cards that produce a wide range of tasks:

The power card (*IFC-PC00*) is used to regulate the power supply to the other cards that will supply the motors and sensors. Power is distributed to the other cards through two ways via side stack connector and external connector.

The computer interface card (*IFC-IC00*) is the main card for IFC cards system, which is used to send and receive data from the other slave cards and the host computer. The computer is able to interface with powerful sensors such as LRF and video camera and by integrating with others IFC cards, it will offer low level control of motors, solenoid, relay, etc.

The brushless card (*IFC-BL02*) is a slave card that is connected to the computer interface card IFC-IC00 and the motor driver card *SmartDrive 40* to control the PWM supplied to the DC-brush motor. This card is able to control two brushless-motor parameters like control of speed, direction, start, stop and braking. It even has a counter for internal speed feedback from the motor driver.

The brush motor card (*IFCBH02*) is a slave card and is used to supply the power to the encoders; also to receive data from encoder.

Output card *IFC-0C04 is used for* interfacing the painting system and navigation system. It is connected through the main controller (*IFC-IC00*) to the on-board computer as shown in Figure 4.9. The output card *IFC-0C04* offers four outputs that can be used to drive the relays or solenoids. In the proposed design, the output card is connected to *SS108T02* relay that operate the pump motor and *SRD-12DC-SL.C* relay that operates the electrical valve. The spray gun stays always open and the spray of the paint is controlled by the signals coming from the main controller to trigger the relays of the valve and the motor of the pump.

3.3 The Differential Drive Unit

The drive unit comprises two differential drive wheels (comprising two 8 in pneumatic wheels) driven by two DC-brush motors (*120W DKM-DC*) and one castor wheel. Other parts on this platform include a battery (*NP7-12* Lead Acid) and the chassis which is fabricated in the laboratory using the aluminum sheets as depicted in Figure 3 and 4.

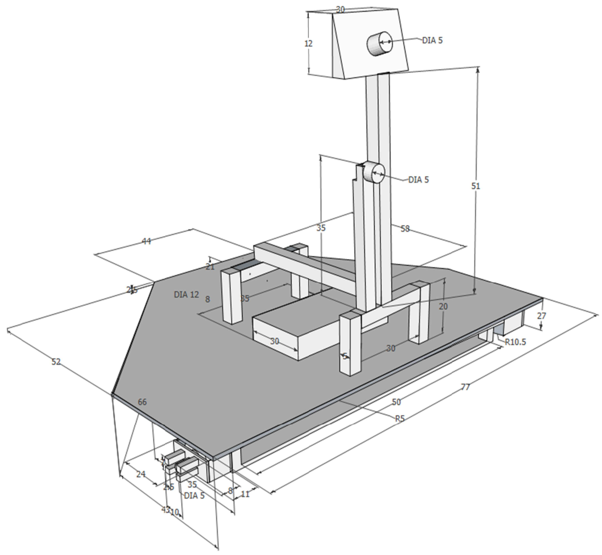

Fig. 3 A 3D model of the WMR platform

3.4 Embedded Controller Design and Setting

It is planned to use the on-board computer as a host controller since A high computational power in this project is required. The LRF and WiFi camera are connected directly to the PC. However, the DC motors and encoders are connected via *IFC-BL02-MDS40A* and *IFC-BH02*, respectively, to the computer interface card *IFC-CI00*. The main power card (*IFC-PC00*) regulates the power supply to the whole embedded controller system. Figure 4.5 illustrates the design procedure.

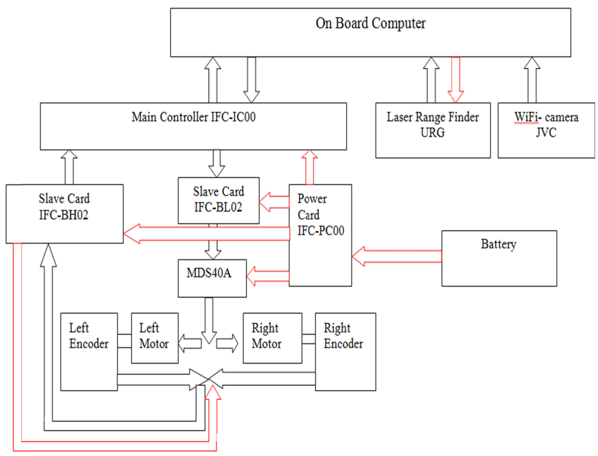

Fig. 5 Flow of data (black) and power (red) in the robot embedded system

The interface computer card (*IFC-IC00*) is the main controller that exchanges the data from host computer to the slave IFC card via stacker pins. The slave IFC cards (*IFC-BLO2*, *IFC-BH02*) are configured to the main controller using a unique communication addresses.

Since the DC motors are controlled using the PMW signal, adequate adjustment was applied to the DIP switches of the *SmartDrive 40*. When the *SmartDrive40* is powered up, the input mode will be read from the DIP switches and retained as long as the driver is powered. The setting of the DIP switches is adjusted to deferential drive mode so that it can control the speed and direction of each motor in the clockwise or anti-clockwise direction. The DIP input data is coming from *IFC-BL02*. The *IFC-BH02* provides the power supply to the encoder which can be adjusted through the mini jumper to 5 V, 12 V or 24 V. It can also receive three signals with 500 pulses per cycle from the encoder for the distance measurement and direction estimation.

3.5 Software Development

The *IFC-IC00* card is compatible with Microsoft Visual C# language which is used to create the graphical user interface as shown in Figure 4.7. The function library for each card is used to form the reference files (in *.dll format). These reference files are uploaded to the workspace to start control/communicate with the IFC cards. Each card will be called by its unique address that has been adjusted with the mini jumper. MATLAB was used for the image and signal processing coming from the camera and LRF since it is a high-performance language for technical computing and has suitable image and signal toolboxes. The linking between C# and MATLAB was done using the COM automation server; data can be created in the client C# program and passes it to MATLAB and vice versa.

4.3 Road Mark Painting System

We will use airless spray pump to perform the painting task. In the spray cold painting as in our system, a high pressure is needed to spray effectively the paint on the road. An airless pump *TITAN-450e* is used for this purpose, which can press the liquid until 214 bar with a flow rate 1.8 l/min. As the motor of pump is supplied by an AC source 240V/6.0A, a DC/AC inverter (*LSM 2000W*) is used to convert the 12 V DC battery voltage to 230 V AC. The manual spray gun (*TITAN-LX-80II*) with multiple diameter nozzles and is always left open in the design. It is a metal construction and has tungsten carbide ball valve and seat to ensure long life and durability. It is equipped with in-handle filter to reduce clogging and increase the tip life, swivel for reducing the hose kinks and effortless control and *517 SC-6* reversible tip. The rated pressure of the valve can reach 210 bar. The spray gun is supported on the platform through a holder that can easily adjust and change the position of gun. A small tank for keeping the paint is attached with the platform. Fig. 8 shows the main components of this system.

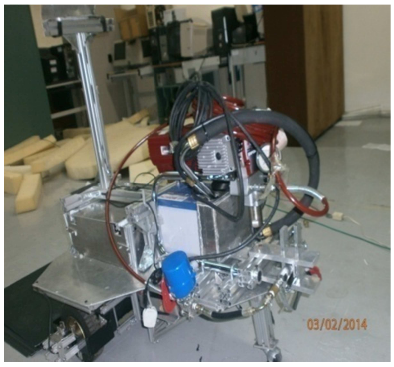

Fig. 8 Components of the painting system on the mobile robot platform

Two interval times T_{on} and T_{off} need to be defined prior to starting of the painting task. The time periods are calculated as a function of the robot velocity and the road lane marking, which determines the length of the spray and the non-painting area on the road as expressed in Equation (4.1). T_{on} indicates the interval time during starting when the spray gun and electrical valve are open, and ends when they close. However, T_{off} specifies the time period for the non-painting task, when the spray gun and the valve remain close.

$$T_{on} = \frac{L_p}{V_m} \qquad T_{off} = \frac{L_r}{V_m} \qquad (4.1)$$

L_p and L_r are the dimensions of the paint and non-paint, respectively for the road lane obtained from the standard catalogue. V_m is the robot velocity calculated by the encoders.

The control of the amount of the paint was accomplished using two methods in the proposed design:

- Switching on/off the pump motor with the time of the spray that calculated using Equation (4.1) in the host controller. This operation is performed using breakout solid state relay *S108T02*. A solid-state relay (SSR) is an electronic switching device, in which a small control signal controls a larger load current or voltage. One needs only to supply a 5 V DC signal to activate the solid state relay and 0 V to switch off the solid state relay.

- High pressure electrical valve: it has been installed between the pump and the spray gun. When the motor of pump is switched off, the paint material is still get out from the spay gun. To solve this problem, a valve near to the spray gun is used which can cut the feeding of paint rapidly. The valve is *AUTOMA-ATM0020* which is equipped with special induction motor that can switch the valve on/off, produces high starting torque and thermally protects from overheating. The valve can be powered by free voltage sources *(*110/220 V AC*,* 50/60 HZ*)* and controlled by (5 A, 250 V AC) signals. The valve is controlled by *SONGLE-SRD12VDC-SL-C* that works with a 12 V DC source and allow to control load with 250V AC and 10 A

4. Autonomous Navigation results

After implementation of a signal processing and image processing algorithms for data as in [6,7], the platform can detect the road curbs in road following in indoor application as follows:

5. Conclusion

The complete mechatronic development of the experimental rig prototype is described. The design and components of a new mobile robot navigation system platform are particularly highlighted. A fully embedded system is realized that integrates the mechanical parts with the electronics and software program, taking into account the path planning, motion control and road mark painting of the WMR system.

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