Control and Guidance of a Pipe Inspection Crawler (PIC)

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Abstract— **Inspection robots are used in many fields of industry. One application is monitoring the inside of the pipes and channels, recognizing and solving problems through the interior of pipes or channels. This ability is necessary especially when one should inspect an underground pipe. In addition, many sensors are used on these robots to improve the quality of inspection, such as vision and nondestructive testing apparatuses. In this work, an inspection robot (PIC) with ability to move inside horizontal and vertical pipes has been designed and manufactured in robotic and automation laboratory of Tarbiat Modares University. Furthermore, different units are installed on this robot, and their functions are examined. Control and guidance of robot in the pipes or channels are discussed. Experiments are arranged to evaluate the mobility of the robot passing through vertical and elbowed pipes. The robot consists of a two DOF camera for monitoring and an ultrasonic unit for measuring the pipe wall thickness. The ultrasonic probe can tough the interior of the pipe in different angle as operator wish. Moreover, the robot outer diameter can be varied and adapted to the pipe inside, to regulate the contact pressure needed between the robot and the pipe. All are being controlled by the operator through a joystick while receiving the video signal of the camera on a monitor. The control system hardware is a microcontroller based with PWM output and A/D converter. The applied forced by the robot are tuned by measuring the current of the motors consume. In addition, the position and velocity of motors are measured by encoders.**

Index Terms— **control, inspection, monitoring, nondestructive test**

I. INTRODUCTION

Inspection robots are kinds of mobile robots which make it possible to inspect inaccessible places by crawling into it and being controlled remotely. So many today's mobile robots are used for inspection, surveillance, monitoring and nondestructive tasks. Some current applications are as below [1]:

- allow inspection of inaccessible and/or hazardous equipment or work areas
- provide on-line inspection/maintenance without loss of equipment/plant availability
- remove humans from potentially hazardous work situations
- provide information about the health and condition of critical plant components to facilitate decision-making regarding plant life management
- reduce equipment/plant downtime
- improve maintenance and inspection procedure thorough better coverage and documentation

The large amount of pipeline use in different industries and the problem of inspecting the interior of them have caused that so many researches concentrate on pipeline inspection robots. Many researches have been done to increase the ability of these robots in inspection. Some of the works attend to conceptive design of robots and implementing new ideas in design like mechatronics [2]. Some other researches concentrate on design of robot and its elements to provide micro-mechanisms and micro-robots for inspecting small diameter pipes [3, 4, 5]. Some part of researches worked on increasing the mobility of robot, accessibility to environment and ability to use different sensors for identification the pipeline interior [6,7,8,9,10]. Some related works have been done to make the inspection intelligent by using fuzzy logic and artificial intelligence [11, 12].

In this paper, the authors present PIC(Pipe Inspection Crawler) which is a mobile robot for inspecting pipelines with 10 to 20 inches diameter. This robot is designed and manufactured in robotic and automation laboratory in Tarbiat Modares University. Design and manufacturing of the mechanism is in order to provide a mobile robot which could access horizontal and vertical pipes and use the sensors which are placed on robot. Fig1 is an overview of the robot.

II. CONCEPTIVE DESIGN

Pipelines have spatial application in industry. Pipes play an important role in transmitting fluids in main industries and by attention to this that they have a limited life and depend on the fluid they transmit, they can fail, the inspection of them become important. After clearing the necessity of inspection and maintenance of pipelines, we should attend to the quality and quickness of inspection. In this way PIC robot is designed for inspection of more usual diameter pipes i.e. 10 to 20 inches. The interior of horizontal and vertical pipes in this range could be accessed by PIC. Also horizontal pipes by more diameters could be inspected by PIC.

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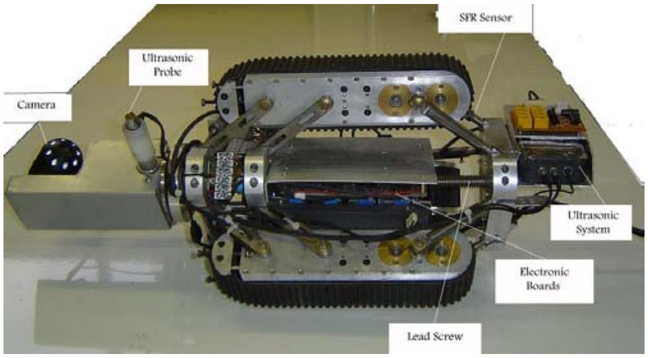

Fig. 1. PIC robot

The mechanism of robot by attention to Fig1, include 3 tracked units which each of them is the third part of a 4-bar mechanism. These mechanisms are placed in a way that they have 120 degrees difference in angle by each other. One stayer of these mechanisms is fixed and another stayer could move by a lead screw. Consequently, by rotation of the screw, the tracked units close or get far from each other. A central DC motor rotates the screw precisely when the robot is moving through bends or probably obstacles. For this reason, this motor includes incremental encoder to facilitate the control of this motor. However, for quick and more suitable moving over small obstacles, the second part of each 4-bar mechanism, have suspension through a compression spring. Regulating the position of tracked units for robot movement through vertical pipes is very important, because on the one hand, if the amount of friction produce by pressuring the tracked unit toward pipe wall is low, the robot could not be stable in pipe. On the other hand, if the amount of mentioned friction become too much, the robot should waste too much power for movement. For being aware of the amount of force between robot and pipe wall, and making decision for increasing or decreasing it, SFR sensors are placed in some rods of the 4-bar mechanisms in attach to compression springs. In producing the PIC robot, manufacturing a modular mechanism which is as small as possible, is considered. So every tracked unit, include a separate dc motor which conclude an encoder. The encoder makes it possible to calculating the robot position in pipe and regulating the speed of movement motors for passing the bends.

The main goal of sending a robot into the pipe is ability to use the placed sensors on robot. One of the main characteristics of inspection robots is their ability to monitor the environment in the best way. Producing a qualified and complete view of environment is necessary for making decision about the system and also implementing other sensors which placed on robot. For this reason a CCD camera is placed on a pan and tilt mechanism which could provide complete monitoring by rotating around in two dimensions. The video signal of the camera, transmitted to a central computer by cable to be watched by operator. Another need in pipeline inspection, is determining the amount of خوردگی in pipe wall. An ultrasonic thickness gage, make it possible to measure the exact thickness of the wall. PIC robot includes an ultrasonic thickness gage which its probe is placed on a 2 DOF mechanism and could reach to the point of wall which operator decides to do the test. One degree of freedom of probe which is about pipe axis is the same as one DOF of camera. Another DOF of probe is moving toward the wall which is independent. The probe could be seen by camera when it moves and so it could be controlled to desired location. Doing the ultrasonic test is very sensitive to get the result. Because on the one hand, the probe surface should completely attach the pipe wall surface. On the other hand, the air gap between these surfaces should be filled by couplant. For the first problem, probe is placed on a flexible joint which could be deviated up to 10 degrees. Consequently, by closing the probe to the pipe wall and increasing the force between two surfaces, the probe become completely adapted to the surface of pipe wall. For the second problem, a miniature mechanism of removing couplant is considered.

The communication between robot and operator is through a computer and by cable. The cable includes power supply wires, video signal wires and control signal wires. The video signal prepared by camera, transfer to the computer and could be watched in monitor after capturing. This image is the base of making decision for operator to manage all the actuators by a joystick. Fig2 presents the general block diagram of the system. Generally the PIC robot provides these facilities:

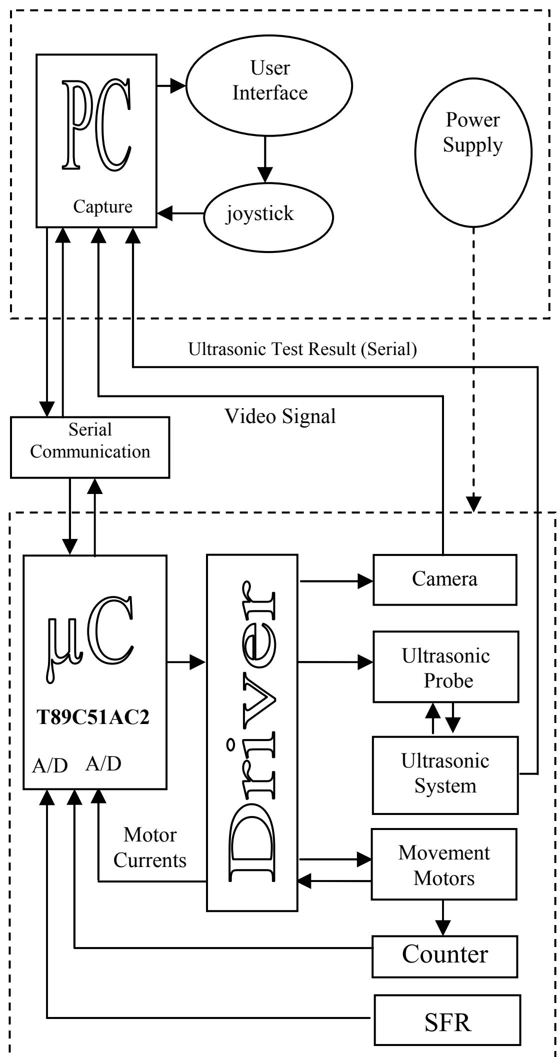

Fig. 2. General block diagram of PIC system

- the robot repots its location on-line
- the camera provide a complete monitoring of pipe interior
- the robot control is through an operator and by transferring signal by cable
- it is possible for robot to pass away pass away the obstacles through the path
- finding the problems and their location is possible by the sensors placed on robot
- measuring the pipe wall thickness is possible by an ultrasonic thickness gage

III. Design of robot different units

In this section, design of different units will be explained. It includes:

- selection of robot actuators
- selection of communication protocol
- design of electronic boards
- monitoring system design
- design of ultrasonic test system
- design of guidance system
- software drivers design

A. Selection of robot actuators

All of the robot actuators are dc gear motors. These actuators are simple to drive and produce dc voltage. By attention to this that power supply in practical sites of robot application is prepared by batteries, these actuators become more efficient. Selection of these motors has done by estimation of maximum load which a motor should handle and also by considering a safety ratio for mechanical inefficiency and inefficient load distribution on actuators. The actuators for movement of camera and ultrasonic probe do not handle so many loads. So in their selection, the volume of the motors was more important. For estimating the critical load of movement motors, the situation of passing vertical pipe is considered. In this situation, by calculating the robot weight, the load by carrying cable, and the acceleration needed in start of moving, one could estimate the amount of friction force needed between pipe wall and tracked units. By calculating this force, the torque applies to movement motors calculate directly. Amount of load apply to central motor of robot is estimated through amount of force that produced on lead screw from the forces apply to tracked unit. By this force, the torque which is needed to rotate the lead screw and consequently the maximum torque needed by central motor is calculated.
The velocity control of motors is done by PWM (Pulse Width Modulation) method. In PWM method, the voltage signal apply to the motor is quadrate. The ratio of high voltage to low voltage in a period is modulated and the mean voltage become regulated. So the velocity which depends on voltage could be controlled. In this method, the frequency of PWM pulse should be more than frequency response of motor. In addition to this, the motor torque in stall situation could be controlled by this method. This way is considered for regulating amount of pressure between probe and pipe surface. The selected frequency of PWM signal is 4 KHz.

B. Communication protocol

The kind of communication between PC and robot is serial and based on RS-232 protocol. In this protocol maximum baud rate, maximum length of wire, kind of signals, their property and definition and also physical ports and their property is defined. The maximum distance for controlling PIC robot is 100 m. Table.1 give an overview of relation between baud rate and the maximum allowable length of cable. The baud rate of communication for PIC is 4800 bps. The guidance signals which send to robot are hex codes. Every code is related to a special work, such as driving different actuators, registering or sending the amount of motor current, ultrasonic test result and SFR sensors data.

TABLE I
ALLOWABLE WIRE LENGTH TO BAUDRATE

Maximum cable length (ft)	Baud rate
50	19200
500	9600
1000	4800
3000	2400

C. Electronic boards design

The electronic boards of robot are a control board and a driver board. The main part of the control board is a microcontroller of 8051 family, the T89C51AC2. This microcontroller, in addition to serial communication and different interrupt routines, include 5 PWM output, 8 analog inputs and watchdog timer which are all necessary for this application. This board has other elements which facilitate microcontroller and PC communication, selection of A/D channel and registering the signals. Another part of this board is FPGA ICs which are capable to be programmed and convert to digital ICs. For our application, these ICs are used as 16 bit encoder counters.
The encoders of robot are incremental. Output channels of each encoder are two quadrate pulses which have 90 degrees phase difference, which depend on direction of rotation, one is forward. These ICs work as 16-bit quadrature counters. Related to direction of rotation, they count up or down.
The microcontroller program is based on serial interrupt. By serial interrupt in this program, the received code is recognized and the part of program related to that is executed. Fig4a shows the control board.
The driver board, drive the actuators by receiving the signals that control board produce. Driver board should be able to drive motor in two directions. So its structure includes H-bridge for each for each motor. Fig 3 shows an H-bridge. This structure has four switches which their state determines that motor rotate CW, CCW or become in brake. The switches are transistors and PWM signal apply to one of the loop switches. Drivers usually have a output for monitoring the driver current.

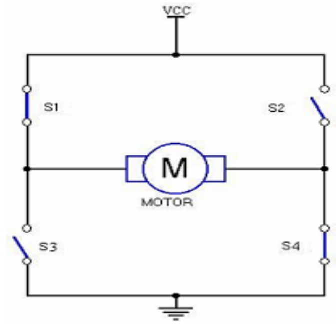

Fig. 3. H-bridge circuit

This output is a voltage that its value is proportion to current value. For driving low power motors of robot, L293 ICs are used. These ICs include two H-bridge and can drive two motors. By increasing the current, downfall of this IC voltage increase. Other driver ICs like L298 and 33887 behave in a similar way. In PIC robot, large amount of downfall could not be survived. Because the power supply is settled on 12 V and large downfall do not allow us use maximum power of motors. So, for high power motor drives, the H-bridges are constructed by power mosfets. Fig4b shows the board which is constructed by power mosfets.

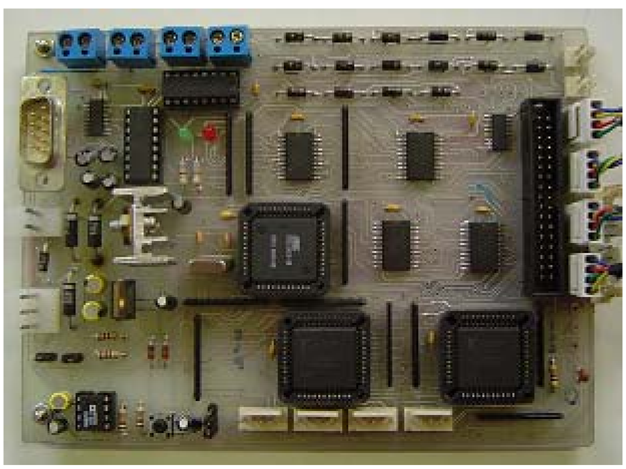

Fig. 4a. Control board

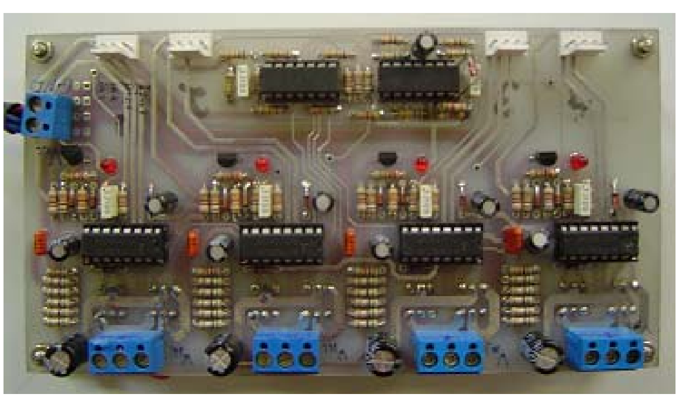

Fig. 4b. Driver board

D. Monitoring system design

The main goal of sending robot to pipe line is monitoring inside the pipe with vision sensor. The image of the pipe wall is prepared by a CCD camera and transmits to the PC through a cable. The kind of camera signal is video and become captured in PC. The quality of the camera image varies by the camera quality. For special inspections, qualified cameras with high resolution and ability to zoom and focus could be used. Control of these specifications is possible by control board.

Another parameter for producing image with good quality is amount of environment light which should be controlled. By attention to this camera can rotate and its distance from pipe wall varies, the light reflection differs. So, the intensity of robot lights should be controllable. This work is done by a board which regulates the voltage of lights after receiving command signals of microcontroller. The operator could control the intensity of lights when view the transmitted image in the monitor.

E. Ultrasonic test unit

Another specification of PIC robot is its ability to implement ultrasonic test for determining thickness of the pipe wall. This unit does the ultrasonic test by attaching pipe wall with the probe, where the operator decide and guide it. The ultrasonic probe includes a pair of receiver and transmitter transducers near its surface. When the probe contact a surface to measure the thickness, the transmitter sanded waves, move through the surface and become received after reflection on separation surface. The wave velocity on desired material is settled on ultrasonic system and by measuring the time of sending and receiving a pulse, system determines the thickness of material.

Another important thing in ultrasonic test is attachment of probe and surface. For this reason, the probe is placed on a flexible joint which could be deviate 10 degrees in every direction. After attachment of probe and surface, by adjusting the PWM duty cycle of related motor, the probe deviate and match with the surface.

The other point for getting a good result in ultrasonic test is filling the air gap between probe and test surface. Because the wave should go through the test surface efficiently and air gap dissipate large amount of wave. Consequently a couplant is used to fill the gap. In PIC robot a miniature mechanism which work by a small motor, remove cuoplant on the probe. The dc motor rotates a screw which moves a piston in a cylinder contains couplant and tend to removing it. The ultrasonic test result, could be saved on ultrasonic system and transmit through serial communication. Unfortunately the available ultrasonic systems setting could not be managed through serial communication and they could be set by their bottoms. For this problem a board based on relays is designed which by the commands of microcontroller, ultrasonic system setting could be managed.

F. Command unit

This unit is considered to transfer operator commands to robot. Command unit consist of a 2 axis joystick that control all actuators of the robot. This joystick communicates PC through USB port. Its driver is set up on PC and software provided on PC, could access the dll files of the joystick. Every action of the joystick could be defined to produce a special code. Joystick axis could be divided to definable steps that by each step of movement that code produce. Also each bottom of joystick could be defined for a special code. The axis and bottoms of joystick are limited, so the commands for driving the actuators are mixed of moving axis and pushing different bottoms. The commands of joystick include:

- controlling the velocity of movement motors for moving forward or backward in straight or bend pipe
- controlling the motors of camera mechanism
- ultrasonic probe movement control
- controlling force between robot and pipe wall
- command of removing couplant

G. *Software drivers*

First part of software drivers is the program of microcontroller. The program logic is receiving PC commands through serial communication and driving the system. The second part is FPGA program which is designed to count the encoder pulses. The last part is the PC software which receives the operator commands, produce serial commands for sending to microcontroller, monitor the robot status and show the image of the pipe interior. Some part of control command like controlling the ultrasonic system is done by pushing bottoms in the graphic interface of the software. In this software the current of motors and SFR forces is reported on-line.

IV. TEST RESULT

PIC robot tested successfully for movement in horizontal and vertical pipes. Fig5 shows the robot moving in vertical pipe. The robot has a good mobility and ability to pass over small obstacles. The important thing is the amount of force between robot tracked units and pipe wall. Even in horizontal moving, attachment of the up tracked unit in addition to bottom ones, improve the movement of robot. Because in this state 3 motors participate in robot move although friction is more. In addition to this, the robot is more stable and distribution of load on different actuators is more similar.

Monitoring the pipe inside was suitable and the control of different actuators was effectively possible. Transmitted image and status data like SFR forces and motor currents help operator to make decision.

V. CONCLUSION

In this paper a mobile robot for inspection task considered. Many challenges have to be removed to provide this product. Complex emissions like ultrasonic test made the work more delicate. Good conceptive and element design could manage all the problems.

The types of inspection tasks are very different. A modular design was considered for PIC that can be easily adapted to new environments with small changes. Different control algorithms could be executed on this manipulator. However, improving sensoring system like force sensors could improve the robot control.

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