DEVELOPMENT OF ROBOTIC SYSTEM

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INTRODUCTION

In this paper we present an innovative design of a robotic system developed for the installation of magnetic markers into the roadway pavement. These magnetic markers are used to provide reference signals for the guidance and control of vehicles on the roadway in an Intelligent Transportation Systems (ITS) environment. Two important aspects of much of current research in developing ITS technologies are improving safety and mobility on the nation’s highways.

Harsh winter environments provide some of the toughest challenges to mobility and safety on the roadways. In bad weather conditions, snow covers roadway markings and edges producing the so-called "white-out" conditions causing cross-lane and runoff-the-road crashes. Although the roadways can be blocked for the general public during such white-out conditions, snowplow operators have to work in such conditions to clear the snow off the roadway. To respond to this situation, several research teams have recently been working on developing an ITS solution to the snow plow operations. These include the work at the University of Minnesota in conjunction with the Minnesota Department of Transportation and others and our work within the Advanced Highway Maintenance and Construction Technology (AHMCT) research center at UC—Davis. This latter work is being performed in collaboration with the California Department of Transportation (Caltrans) and the PATH (Partners for Advanced Transit and Highways) program at UC—Berkeley.

The snowplow work in California, to date, has focused on using magnetic reference markers on the roadway pavement to provide the necessary reference signal for driver assistance and vehicle guidance. The use of magnetic reference markers on the roadway surface has also been demonstrated for automatic control of vehicle during the national Automated Highway System Consortium (NAHSC) demonstrations in San Diego, California in 1997. Installation of the magnetic markers into the roadway pavement, however, is a tedious manual operation. In this paper, we present the mechanical design of a robotic system that is under development in our laboratory that will mechanize the installation process of these magnetic markers. This robotic technology, once deployed, can facilitate the further development and use of ITS technology based on this type of magnetic sensing on the Nations’ highways

Literature Survey

1. Robotics and Automation Applied to Caltrans Highways by Professor Bahram Ravani Advanced Highway Maintenance and Construction Technology (AHMCT) Research Center. (A partnership between the University of California - Davis and the California Department of Transportation)
3. ROBOTIC SYSTEMS for DEPLOYING SENSORS to DETECT CONTRABAND in CARGO (M. W. Siegel Measurement and Control Lab — The Robotics Institute School of Computer Science and A. M. Guzman and W. M. Kaufman Carnegie Mellon Research Institute, Carnegie Mellon University)
4. Design Considerations for Manipulator Workspace by K. C. Gupta (Associate Professor, Department of Materials Engineering, University of Illinois at Chicago Circle, Chicago, III. Mem., ASME) & B. Roth Professor. (Department of Mechanical Engineering, Stanford University, Stanford, Calif.)
6. CAD/CAM/CIM by P. Radhakrishnan (New Age International Publs.)

Review of Literature:

Robot Definitions:

1. Robotics Institute of America (1975): An industrial robot is a reprogrammable, multifunctional manipulator designed to move materials, parts, tools, or specialized devices through variable programmed motions for the performance of a variety of tasks.
2. Webster’s Dictionary: A robot is an automatic apparatus or device that performs functions ordinarily
ascribed to humans or operates with what appears to be almost human intelligence.

3. Webster’s ISO (1988): “An industrial robot is an automatic, servo-controlled, freely programmable, multipurpose manipulator, with several axes, for the handling of work pieces, tools or special devices. Variably programmed rammed operations make possible the execution of a multiplicity of tasks”.

4. IFToMM (1991): A robot is a Mechanical system under automatic control that performs operations such as handing and locomotion; and Manipulator as Device for gripping and controlled movements of objects “locomotion”.

5. IEEE Community (2000): “A robot is a machine constructed as an assemblage of joined links so that they can be articulated into desired positions by a programmable controller and precision actuators to perform a variety of tasks”.

**Terminology:**

**The Word Robot:**
- From Czech word Robota for forced labor or compulsory service
- 1st appeared in “Rossum’s Universal Robot s Robot” (R.U.R) a Czech play by Karel Capek (pronounced “chop-ek”).

**R.U.R opened:**
- Prague 1921, New York 1922, London 1923
- 1920 translation by P. Selver available as Penguin series from Dover
- More recent translation is contained in translation of a collection of Capek’s writings called Towards the Radical Center. Isaac Asimov (1920 – 1992) introduced the term robotics in his story Runaround published 1942.
- Asimov is credited with popularizing the concept of robotics through a series of short stories about robots starting with a story called “A Strange Playfellow” which he wrote for Super Science Stories magazine.
- This story is about a robot and its affection for a child that it is protecting. He later renamed this story calling it “Robbie”.
- Asimov generated many other stories about robots which are compiled into a book volume called “I, Robot” published in 1950.

**Asimov:**
- First Law: A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.
- Zeroth law: A robot may not injure humanity, or, through inaction, allow humanity to come to harm.
- Third Law: A robot must protect its own existence as long as such protection does not conflict with the First or Second Law.
- Zeroth law: A robot may not injure humanity, or, through inaction, allow humanity to come to harm.

**What is AHMCT?**

The Advanced Highway Maintenance and Construction Technology Research Center (AHMCT) extends the reach of Caltrans with technology, analysis, and communications.

We are primarily a project oriented research center on the campus of UC Davis that develops concept vehicles and equipment for the California Department of Transportation. AHMCT has delivered 16 vehicles and 18 pieces of software and equipment to Caltrans.

We also help Caltrans access university and industry research, maintain a leadership position in maintenance and construction technology, access federal and pooled funds for research, test and evaluate new technologies, improve the Caltrans public image as a technology oriented organization, and train students and professionals in transportation operations and technology.

Innovative technology can keep workers in vehicles for many highway maintenance tasks or behind barriers for other tasks. Also, tools exist to make on-the-ground lifting, moving, cutting, filling, and clearing tasks easier and safer. Key off-the-shelf technologies include computers, robotics, sensors, interfaces, GPS, GIS, communications, databases, materials, and hydraulic.

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and pyrotechnic heating methods were promising alternatives to the existing bitumen marker adhesive process. The two methods were further investigated during the extension with an attempt at further improving heating rate and bond strength of bituminous adhesive.

The results from the extension work showed that the induction heating method is very close to the practical application for an automatic RPM machine. However, several areas, such as arcing and damage on the reflective surface, need to be resolved prior to integration of induction heating technology into the automatic RPM machine. Further study on both induction and pyrotechnic heating is strongly recommended. It is suggested that the further investigation and development will be carried out directly by the private sector such as Hellerbond, an induction heating company, and RISI, a pyrotechnic company.


In past few years, research efforts have been made to automate the marker placement process in order to increase operator safety and minimize traffic hazards caused by the current manual process. Several automatic raised pavement marker machine (RPMM) prototypes have been developed and tested. The concept of automating the marker placement process was proven. However, the bulk adhesive melting method was found to be difficult and almost incompatible with the automation of marker placement. The handling of liquid adhesive is messy and often contaminates and malfunctions robotic components or the end-effector. Delivery of hot bitumin at ca. 204.4 degrees C (440 F) also creates safety problems and causes unnecessary wear of mechanical parts. Hot bitumen dispensing system is prone to high maintenance and easy failure, the resulting start-stop process requires a long down time, therefore lowers productivity.

In order to increase reliability and maneuverability of the automatic RPMM, a research has been conducted at University of California, Davis under the contract with Caltrans. This research investigates new marker adhesive processes aimed at eliminating the on-road bitumen melting and handling. With the proposed marker adhesive processes, markers are pre-attached with the adhesive layer on the bottom during manufacturing, laid onto road by the automated RPMM, and the adhesive layer will be then locally processed (with or without heating) to adhere to the pavement. The investigations performed were grouped into two categories, i.e., localized heating approach using bituminous adhesive and new adhesive material approach. New adhesive process methods and materials were investigated in close cooperation with Caltrans laboratories as well as adhesive and marker manufacturers including Stimsonite, Crafco, Davidson, Hellerbond, and RISI.

In Traffic Jam IVC - RVC System for ITS using Bluetooth, by Akihiko Sugiura and Candra Dermawa.

In the Intelligent Transport Systems field, research continues In-Vehicle Communications, Inter-Vehicle Communications, Road-to-Vehicle Communications etc. All information communications technology, especially radio-communications technology, was applied. This paper, to minimize the costs of equipments, simplify a design, equipment, structure of all the systems communication for traffic jam area, we proposed to utilize a wireless Bluetooth technology system. The whole systems we proposed is connected to the Internet backbone provided some access point area, the Internet can be accessed from inside the vehicle and information, such as news and weather information can be downloaded. It is also possible to know traffic information for each access point area by accessing a data center server. Further more we developed Bluetooth-based IP phone service application. So the whole system, not only for transferring static or dynamic picture but also for voice communication can be performed

Workspace of a Point:
One way of defining the workspace of a manipulator is as the aggregate of all possible positions of a point attached to the free end of the manipulator. This point is usually located at either the center of the "wrist," the center of the "hand," or the tip of a "finger."

Accessible Region and Synthesis of Robot Arms:
A brief survey of the existing literature reveals that the review trends in the design, developments and manufacture of robots and manipulators may be divided into the following categories:

(a) Design of robot or manipulator systems satisfying prescribed functional requirements.
(b) Static kinematic and dynamic of force analysis of a robot or manipulator system.
(c) Performance analysis of remote manipulator systems.
(d) Design and development of manipulator using touch sensing, or proximity sensor as feed-back control.
(e) Application of control theory for robots and manipulators.
(f) Application of the robotic and manipulator – design science in developing artificial limbs for the disabled or to solve industry man-power problems.
The present literature permits one to identify the area that demands research priorities in the science of kinematics as applied in the kinematic synthesis of robots or manipulators. Some of these research priorities are:

(a) Classification of one or two-arm robots having lower kinematic pairs, such as revolute pair, prism pair, hexical pair, cylinder pair, spherical pair etc.

(b) Geometry of motion and task classification of robots and manipulators.

(c) Kinematics and dynamics of open-loop kinematic chains simulating robots and manipulators.

(d) Application of the above in synthesis of a robot or a manipulator. Once the classification of single loop kinematic-chain has been developed, the problem studying the geometry of motion and task-classification needs to be investigated. The geometry of motion involves studying the accessible region of a given robot or manipulator.

The Accessible Region and Synthesis of Robot Arms deals with the following problems on accessible regions:

(a) Developing a general method for determining the accessible region (area) of industrial two-link and three-link robots in planar case.

(b) Synthesis of two-link and three-link robots which can reach some specified planar point path or rigid body positions.

(c) Application of accessible regions concept to coupler curve generation and mechanism synthesis.

**NEED FOR ROBOTICS AND AUTOMATION:**

The purpose of this paper is in part to advance the concept that the functional problems of existing methods can be overcome by using computer control of the machinery to automate the boring, uncomfortable, time consuming and error prone aspects of the inspector’s job. We also suggest that at the same time the safety shortcoming of existing instrumentation can be overcome by using remotely operated machinery to separate the inspector from the instrument.

Mobile robots similar in mechanical complexity, remote controllability, and degree of local autonomy to those that will be needed for contraband detection are already in use in other applications. We will discuss one of these applications, aging aircraft inspection, in depth later. The flexibility and extensibility of the robotic approach, illustrated by the ease with which these concepts can be transferred across applications, will permit systems built along the lines discussed here to keep up with evasive maneuvers that will emerge in narcotics smuggling technology as the detection technology improves.

Robotic approaches to deployment of established detection technology would wisely be the first step of a broad program to make systematic improvements in the effectiveness of a range of contraband import, export, and domestic shipping policing efforts. These might include, in addition to narcotics, substances such as explosives and ammunition, special nuclear materials, strategically important metals, as well as restricted agricultural products, electronic components and assemblies, etc.

The application of similar technology to a variety of problems that share the need to make "difficult measurements in difficult environments," each with unique features that can be individually addressed in a common framework, presents an opportunity for synergistic technical and economic improvement across the board.

**SYSTEM FEATURES:**

Several mechanical design concepts for mobile teleoperated and semi-autonomous manipulators aimed specifically at the narcotics-in-cargo container threat are sketched in Figure 1. The "side sucker" design, using suction cups to adhere to the exterior of a cargo container, is in the same spirit as the robot (described later) we are building for airplane skin inspection. However, unlike airplanes, cargo containers are often dirty and dented, making adhesion difficult. Thus the "rail rider" sketch, suggesting a mobile car wash, would probably be a preferable technology for an early contraband interception demonstration. With the "rail rider" design we would have the option to deploy at least three instruments simultaneously, one each for the left and right vertical walls and one for the top. If the top rail were to ride up and down on the two vertical rails then the top sensor package could inspect the front and back faces of the container as well. This implementation would easily also accommodate a variety of container sizes.

The mobile robots would be integrated with a suite of proven detection and sensing technologies, using established observation-plus-context based procedures for path planning, guidance, and world model building. A combined color TV and computer graphic human interface would report the instrument’s findings via contour maps, special symbols marking suspicious areas, with printed numerical data and appropriate highlighting superimposed on live images of the actual container under inspection. In one operational scenario a supervisor, working at the display, dispatches inspectors to suspicious containers.

The inspectors carry color prints of the display, rapidly guiding them, by images and coordinates, to the suspicious areas of the suspicious containers. They proceed with their own familiar methods of tapping, drilling, unloading, etc, and also have the option of
obtaining additional data from the instrument. The immediate localization to a specific area of a specific container might enhance by a hundred or more the throughputs and the seizure rates that are credited to the inspectors. The machines do what machines do best, the tedious, uncomfortable, and dangerous work. The inspectors do what intelligent people do best, flexibly exercising human judgments. Cost effective deployment requires being able to predict which containers are most likely to be carrying narcotics, and concentrating the machines and the people on those containers.

The inspection technology that we conceive incorporates electronic command, communications, and computing components that will automatically build a performance database. It will be natural to combine this program with research toward improving the statistical and heuristic (artificial intelligence) methods available for using the database to guide resource deployment decision making.

**THEORY**

3.1 IMPLEMENTATION

**Magnetic Reference Marker Installation:**

Magnet installation involves drilling the roadway surface to a predetermined depth, orienting the magnet for correct polarity, inserting the marker into the roadway, and finally sealing the magnet into the roadway pavement. At present, four stacked ceramic dipole magnets approximately 22.1 mm (0.87 in.) in diameter by 25.4 mm (1 in.) thick are placed just under the road surface to provide the desired magnetic field in normal roadways. On roadway structures such as bridges and overpasses, a single Neodymium magnet 25.4 mm (1 in.) in diameter and 19 mm (0.75 in.) thick is used. The single neodymium magnets are strong enough to provide the necessary magnetic field to ensure proper detection.

The number of magnets inserted at each location determines the drilling depth. Stacked ceramic magnets and the neodymium magnets require hole depths that are just over 10.1 cm (4 in.) and 2.5 cm (1 in.), respectively. The insertion should be such that the top of the magnetic reference marker is between 0 and 1 cm (0.39 in.) below the roadway surface. Furthermore, the angular tolerance, or deviation from perpendicularity, to the road surface should not exceed ±2°. The magnetic markers are placed 1.2 m (3.9 ft.) apart longitudinally and centered (within the lane) laterally. Because vehicles depend on the magnets for speed detection and lateral road position, magnet placement is crucial and proper location tolerances must be met. Surveying methods are used and proper positions on the roadway pavement are premarked for magnet insertion. A crew of several people is used to position a drill at the premarked location and drill a hole into the pavement.

![Fig. 1: Manual installation of magnetic markers.](image)

A sealant is then applied to the drilled marker cavity and the magnets are inserted manually and checked for proper orientation and the depth below the road surface. The sealant secures the magnet to the walls of the cavity preventing linear and angular movement and it also waterproofs the roadway surface by preventing water to go under the roadway surface, causing delamination of the pavement during freezing.

The robotic system to automate this process must have the freedom to move independently in both the longitudinal and lateral directions on the roadway. It must also be equipped with control over the drilling depth (z axis). Control over angular tolerances may be accommodated by calibration during assembly of the drilling mechanism.

The system has to be able to move above the roadway surface and reach vertically to different insertion depths. It is also required that the system be independently towable with a pickup-size truck. These requirements are consistent with a gantry robotic system mounted on a trailer. There exists a rather large body of work on robotic design based on workspace considerations. Here workspace considerations are simple leading to a gantry system design.

The system as developed is shown in Figure 2. It is a specialized gantry-type robotic system mounted on a trailer bed. It consists of a conglomeration of several subsystems that are described in the subsequent sections. The trailer bed was chosen to provide enough room to carry the necessary power and other needed materials for turnkey operation of the system. Figure 3 provides an overview of the trailer system with all of its subunits, which consist of the gantry robotic marker installation system, a power generator, an air compressor, magnet, and epoxy storage units. Two critical component technologies were identified as key requirements of the robotic system.
The storage units are used as part of the material handling system to deliver the sealant (epoxy) and the marker (magnets) to the end effector of the robot. A detailed description of the system and its operation is provided later.

One was the drilling unit that had to be designed such that it would be able to isolate the robotic system from excessive vibrations during drilling of the pavement. The second was the linear drive system for the two linear axes of the gantry that had to be designed such that they would work in the presence of debris and potential small deformations of the gantry axes that can occur in harsh roadway environments.

A subcritical component was the structure of the system that had to provide the needed structural strength necessary for reliable operations. The designs of these three critical and sub-critical components are described in the next three sections.

Dynamic considerations were considered by Asada and Kanade in their design of the direct drive arm, but they emphasized mass distribution rather than vibration isolation and damping. Here it is shown that vibration isolation and damping play key roles in the design of this robotic system.

3.2 METHODOLOGY: Drilling System Design and Vibration Considerations:

The drilling unit should accommodate both concrete and asphalt roadways. The hard, brittle nature of concrete favors an impact-(hammering-) type drilling while softer, asphalt substrates requires more of an auguring process to continuously remove debris without excessive heating. Therefore, the drilling method chosen was a combination of auguring together with impact hammering. Rock drills are available in various sizes and combine the twisting of an ordinary drill with the hammering action of a jackhammer. The addition of an air stream through the center of the drill makes this a combination well suited to drilling both asphalt and concrete surfaces and was chosen in the design of the robotic system.

A key factor in the design of the system is minimizing transfer of the vibration during the drilling operation to the rest of the robotic system. The prototype drilling unit was assembled and outfitted with an accelerometer, as shown in Fig. 4. With its own power supply and an adjustable gain, the accelerometer could be connected directly to an oscilloscope.

Initial readings did little except to confirm that a large portion of the measured signal was in the range of audible noise. The manufacturer data reports sound energy at 116 dB. Correspondingly, a 100 Hz low pass filter was placed between the accelerometer and the oscilloscope to reduce unwanted “sound” energy in the vibration signal.

As the hammering action of the drill was expected to reside in the 30 Hz range there was no concern about degrading the signal of interest due to the filter. After implementation, the accelerometer/filter combination produced the data presented in Fig. 4, object 3.
As expected, objects 3 and 4 of Fig. 4 show a signal with a period of approximately 0.03 s that corresponds to a frequency of 33 Hz. Object 4 of Fig. 4 shows the mathematical implementation of a second-order Butterworth filter with a crossover frequency of 300 Hz. This additional filtering was implemented using signal processing routines via MATLAB.

The impetus for the computational filtering was the desire to obtain a better approximation of the wave shape. Any mathematical models would require a comparison to well-filtered data due to high-frequency components assumed to be negligible when constructing the model. In order to obtain the frequency composition, the signal was subject to a Fourier Power Spectral analysis, which further confirmed the fundamental frequency of the signal at approximately 30 Hz with a frequency resolution of 2.5 Hz. More importantly, the spectral analysis also revealed the harmonics associated with the signal. As shown in Fig. 5, the harmonics of the rock drill data are spaced at about 30 Hz intervals and decrease in magnitude rapidly.

Studying the relative magnitude of the first and second harmonics, it is clear that the first harmonic is approximately three times that of the second. This largest pure frequency component making up the vibration signal should be attenuated with a single vibration absorber or by proper choice of adequate damping. A Tuned Vibration Absorber (TVA) may be used, for example, to remove or attenuate this large frequency component. In order to achieve this, the excitation signal of a system with a TVA must be relatively sinusoidal and at a single frequency. Attacking the frequency with the most energy may reduce more complex signals, such as a sawtooth or triangle wave, but will not remove their effects completely. It seems therefore that partial elimination of the first harmonic by use of a TVA may provide for a significant reduction in vibration energy. It must also be noted that the frequency specific nature of a TVA may attack only a narrow bandwidth around the first harmonic. Due to excessive vibrations experienced while testing the drill candidates, a general lumped parameter dynamic model was constructed and outfitted with a TVA. The model shown in Fig. 5 consists of a drill mass, \( m_a \), additional absorber mass, \( m_a \), spring, \( k \), and damper, \( d \). Further, this linear model can be written in the form given by Eq. (1), thus allowing for the development of transfer functions, which in turn yield critical frequency related behavior.

\[
\dot{x} = Ax + Bu
\]  

(1)

Fig. 5: Drill-TVA Model.

By selecting an appropriate value for \( m_a \) and \( k \) the absorber mass can be made to vibrate 180° out of phase with the sinusoidal drill input \( f(t) \). In so doing, the force propagated through the absorber spring and damper acts to reduce the vibrational displacement, \( x_d \), of the drill. These and other system parameters are outlined in Table 1.

**Table 1: Drill — TVA system parameters and values.**

<table>
<thead>
<tr>
<th>System parameter</th>
<th>Symbol</th>
<th>Value (SI - units)</th>
<th>Value (US- units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Absorber mass</td>
<td>( m_a )</td>
<td>4 kg</td>
<td>8.8 lb</td>
</tr>
<tr>
<td>Spring constant</td>
<td>( k )</td>
<td>157 kN/m</td>
<td>895 lb/ in.</td>
</tr>
<tr>
<td>Drill mass</td>
<td>( m_d )</td>
<td>35 kg</td>
<td>77.2 lb</td>
</tr>
<tr>
<td>Damping</td>
<td>( b )</td>
<td>30 N/(m/s)</td>
<td>0.3 lb/(in./s)</td>
</tr>
</tbody>
</table>

As indicated earlier, the drill vibration is not purely sinusoidal; nevertheless, by tuning the TVA to the fundamental frequency of vibration, some attenuation can be expected. Test results demonstrated the fundamental drill harmonic to reside at approximately 30–33 Hz. The absorber frequency is then given by Eq. (2).

\[
f = \frac{1}{2}X(m/k)^{1/2}
\]

(2)

Utilizing the fundamental drill frequency, reasonable values were chosen as 157 kN/m (895 lb/ in.) and 4 kg (8.8 lb) for the spring constant and absorber mass, respectively. Given these values, Eq. (2) yields 31.5 Hz as the TVA frequency. The knowledge that a perfect spring does not exist in reality imparts the inclusion of damping in the TVA model.

The introduction of the TVA also has an unwanted effect. With two masses interacting with the absorber spring, the system exhibits two resonant frequencies. One is exploited by the TVA to calm the vibration of the drill, given by Eq. (2), and another arises when the characteristic equation, given by Eq. (x) approaches zero. It should be pointed out that the damping, \( b \) (although absent from the TVA frequency equation) also plays an important role in the behavior of the system. Equation (x) is the characteristic equation for the system in Fig. 5 and thus is the denominator for all transfer functions of this system. The nontrivial roots to Eq. (3) are given by Eq. (4).

\[
(s I - A) s^2 + (b/(m_a + b/m_d)) s^3 + (k/(m_a + k/m_d)) s^2
\]

(3)
As shown in Eqs (3) and (4), the damping does affect the characteristics of the system by acting to reduce the “peaks.” It must also be noted that while reducing the unwanted displacement of the drill, the damping has little effect on the TVA bandwidth. Although the added damping does help to reduce the resonance just above the TVA frequency illustrates that it also reduces the amount of TVA attenuation at the frequency given by Eq. (2). Other means were explored to increase the bandwidth of the TVA due to this undesirable attribute.

\[ S_{1,2} = \frac{1}{2} (b/m_a + b/m_d) \pm \frac{1}{2} \sqrt{(b/m_a + b/m_d)^2 - 4(k/m_a + k/m_d)} \]

(4)

Examining Eq. (2) it is clear that by proportionally increasing \( k \) and \( m_a \), the natural frequency of the TVA will remain unchanged. This idea was implemented by introducing an amplification constant, \( a \), into the original Amatrix for every \( k \) and \( m_a \). The new equation for the resonant frequency is then given by Eq. (x), and its effect on the bandwidth can be seen in Fig. 6.

The amplification factor approach seems promising at the first glance. The resonance predicted by Eq. (x) is moved further from the TVA frequency along with a recovery of attenuation losses due to the addition of damping. The increase bandwidth of the TVA appears now to encompass the full first harmonic. The effectiveness of the original versus the increased bandwidth TVA can be easily distinguished from Fig. 6. Utilizing –3 dB to designate the operational bandwidth. Figure 9 demonstrates an increased bandwidth with increasing values of \( a \). Problems with the amplification factor approach arise upon examining the “amplified” values of \( k \) and \( m_a \) for implementation. The previous frequency response diagrams illustrate the fundamental TVA with achievable “real-world” values of 157 kN/m (895 lbf/in.) and 4 kg (8.8 lb) for \( k \) and \( m_a \), respectively. Calculating the amplified values, \( a_k \) and \( a_m \), result in a spring constant of 1225 kN/m (6995 lbf/in.) and absorber mass of 28 kg (61.7 lb). This type of vibration isolation would add significant mass and weight to the system, thereby increasing the size of the robotic positioning system and the complexity of its control system. It is therefore clear that a TVA alone cannot be a solution to the problem and the use of additional damping should also be explored.

A new model was developed that included a model of a pneumatic position actuator used for depth control, the drill, and a TVA, as shown in Fig. 7. The inclusion of the position actuator in this new model allowed for the investigation of the damping and decoupling effects that could result from the proper design of the actuator. In this model, the relationship between the air cylinder mass and the drill could easily be evaluated by allowing the TVA mass, \( m_a \), approach zero while holding the value of \( k \) constant. In doing so, the added weight to the system is rendered negligible and the natural frequency associated with Eq. (2) is shifted well beyond the area of interest.

Table 2 summarizes additional system parameters for the drill TVA model with an actuator included. The final values of these parameters were obtained through an iterative process and correspond to values for industrial-type actuators required for this application. Unloaded, many air cylinders, particularly rodless air cylinders, are prone to chattering due to slip stick friction between the sliding carriage and air cylinder during low-speed
In the course of acceleration testing the system, it was noted that the additional drill and mounting hardware mass were sufficient to remove slip stick friction effects, even at low speeds. As a result the friction between the rodless air cylinders and the cylinder carriage was modeled as viscous damping and thereby help to compensate for the previously neglected pipe friction and fluid inertia of the lower cylinder. Upon comparison of the “Drill—No Absorber” response of Fig. 8 and the “No - TVA” drill response depicted, it is clear that the added mass of the pneumatic actuator and mounting hardware has decreased the vibrational displacement of the drill across the frequency spectrum of interest without the use of the TVA. Figure 8 also demonstrates a significant reduction in the drill vibration by use of the original, unamplified, TVA from previous designs. Perhaps most importantly, the response of the pneumatic actuator demonstrates the desirable decoupling effect mentioned previously. Although the implementation of the TVA further reduces the air cylinder vibration, the reduction is not only much less drastic than that of the drill, but also provides an impetus to reconsider the use of a TVA at all. The introduction of a pneumatic actuator into the drill—TVA model provided a means for the mathematical model to simulate the decoupling of the drill with the air cylinder and thus the rest of the system. By simply comparing values of total system mass in Table 2, one would expect a reduction in the vibration amplitude. The frequency response plots shown in Fig. 8 demonstrate this to be the case. Furthermore, the only connection between the air cylinder and the drill is by way of the resistance $R_f$. Without depiction here, additional plots with reduced piston to pneumatic cylinder resistance, demonstrate increased decoupling. Using the above analysis, the drilling unit was designed with two rodless air cylinders to be able to control the drilling depth. The cylinders were sized using the parameters from the simulation discussed in Table 2. Figure 9 depicts the mechanical realization of the drilling system with the two air cylinders. The system shown in Fig. 9 was positioned horizontally to remove unwanted gravitational effects. While in this configuration a force scale was attached to the drill and the cylinders rigidly secured. A horizontal force applied at the scale was slowly increased until movement was detected at the drill. The results showed approximately 222 N (50 lb) to induce slipping and roughly 133 N (30 lb) to maintain slip.

Table 2: Actuated drill—TVA System parameter, values and state variables.

<table>
<thead>
<tr>
<th>System parameter</th>
<th>Symbol</th>
<th>( additional parameters only)</th>
<th>Value (SI units)</th>
<th>Value (US units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air cylinder mass</td>
<td>$m_c$ 65 kg</td>
<td>143.3 lb</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Air cylinder pressure</td>
<td>$P_u$</td>
<td>140 kPa</td>
<td>20 psi</td>
<td></td>
</tr>
<tr>
<td>Piston area</td>
<td>$A_f$</td>
<td>32.2 cm$^2$</td>
<td>2.49 in.$^2$</td>
<td></td>
</tr>
<tr>
<td>Cylinder friction</td>
<td>$R_f$</td>
<td>1300 N/ (m/s)</td>
<td>7.5 lb/ (in./ s)</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 8: Drill and rodless air cylinder response.
This experiment suggested a theoretical maximum force transmitted through air cylinders due to friction of about 222 N (50 lb). Testing of the drilling unit without the air cylinders indicated that the drill may vibrate with a cyclical force of approximately 534 N (120 lb). This means that only 222 N (50 lb) or approximately less than half of this 534 N (120 lb) would actually be transmitted to the rest of the installation system. These test results support the design of the system without the inclusion of a tuned vibration absorber.

**Fig.9: Depth control/drilling (DCD) system.**

**Structural Design:**

Structural design of the system was a subcritical design consideration to support the effect of any vibrations transmitted to the system. The design has to provide the necessary strength while having a weight that can be easily moved with reasonable-size joint actuators of the robotic system. An Upright Support Structure (USS) was designed that integrates the DCD system with the Magnet Transfer and Insertion (MTI) end effector. The USS is secured to the X-Y positioning gantry by specialized Adjustable Preload Clam Jaw Slides. These components provide all of the essentials to accurately position, install, and secure Magnetic Reference Markers in the roadway. In the remainder of this section, we describe USS for the drilling unit. The Roller Type Traction Drive System is described in the next section.

**Fig.10: Upright support structure (exploded).**

The support structure is depicted in Fig. 10 and does provide adequate strength for the drilling unit. The Right and Left Frame Assemblies are fastened to the Twin Slide Securing Plate at the designated brackets and also form a connection through the Rodless Air Cylinders of the DCD system, discussed previously.

**The Roller Type Traction Drive System for Linear Motion of the Gantry Robot:**

In the design of the gantry robotic system, special attention needs to be paid to the design of the linear slides for smooth and proper operations. Maintaining smooth contacting surfaces over the workspace of each axis of the gantry may be difficult in the harsh roadway environments. Debris from the roadway may get deposited on contacting surfaces of the linear slides degrading the motion; or forces from using the system on the roadway after sometime can cause small deflections, deformations, or distortion of the slides, degrading the linear motion. Most of the commercially available linear drives and slides use some form of bearing design that would not overcome some of these problems.

A new concept of linear slides was therefore developed here that would obtain the linear motion from rubber wheel motion against a traction surface. A spring-loaded system would make sure that there is enough traction between the wheel and the surface to avoid slip and would comply with any debris that may be deposited on the drive surface. The design, in concept, is similar, in part, to the drives used in the operation of an amusement park rollercoaster. The rollercoaster bogie works by trapping the track in between urethane roller wheels. This allows for smooth running in the presence of dust and dirt, and low maintenance while holding the rollercoaster cars securely to the track. Design of the carriages for the X-Y gantry developed here uses this idea with I beams as tracks.

The grips of the carriages on the I-beam must be sufficient to remain in contact while drilling or during accelerations of the installation vehicle.

**Fig.11: Adjustable preload clam jaw slide.**
A linear carriage design was developed that incorporated the ability to adjust the amount of preload on the I-beam track through the use of typical compression springs. Figure 11 shows the Adjustable Preload Clam Jaw Slide developed with an appropriate cross section for operational clarity. By interfacing the lower wheel of the linear carriage at an angle, as shown in Fig. 11, the mechanism is able to provide a clamping force due to the moment produced by the compression springs, as well as a reaction force to \( F_s \) thereby ensuring straight line motion, as constrained by the I-beam webbing.

The Compression Springs pull on the Preload Bolts, which in turn apply forces to the top of the Lower J bracket. The bracket pivots on the shoulder bolt and thus applies the desired compressive forces on the I-beam through the inline skate wheels.

The upper roller wheels where designated as readily available 600.5 N (135 lb max) load neoprene roller wheels with a 5.1 cm (2 in.) diameter. Each carriage was designed with three upper rollers, as illustrated in Fig. 11, which gives an overall load carrying capacity of 1801.5 N (405 lb max load). This spring constant was calculated, assuming a 0.32 cm (0.125 in.) initial (preload) deflection, which yields a value of 7206 N (1620 lb)

The lower wheels required a rounded geometry to fit into the interior fillets of the I-beam rails; they needed to be relatively insensitive to dirt, and, most importantly, robustness was essential. As demonstrated by Fig. 12, contemporary inline skate wheels were available in sizes that met the geometric requirements of the I-beam interior radii. These wheels offer many important attributes; they were designed to operate in an outdoor environment, they are regularly subjected to shock loading, they are expensive and easily obtained, and they are available in a variety of hardness.

![Fig.12: Free body diagram for lower cantilever wheels.](Image 70x118 to 280x254)

Two springs provide the preload in the slide assembly through two wheels. The moment arm lengths to the pivot pin, as illustrated in Fig. 13, govern the proportionality constant between the springs and the preload force. The force applied at the contact point of the lower roller wheel can be obtained by equating the moments about the pin:

\[
F_{\text{spring}} = kx_0 \quad F_{\text{spring}} = 298\text{N (67 lb)}
\]

Where,

\[
K = 938.7 \text{ N/cm (536 lb/in.)} \\
X_0 = 0.32\text{cm (0.125 in.)} \\
M = F_{\text{spring}} L_s - F_{\text{lwr.wheel}} L_{w} \\
F_{\text{lwr.wheel}} = F_{\text{spring}} L_{w} \quad L_s = F_{\text{lwr.wheel}} = 285\text{N (64.1 lb)}
\]

Where,

\[
L_s = 4.72\text{cm (1.865 in.)} \\
L_{w} = 4.95\text{cm (1.950 in.)}
\]

Using the vehicle acceleration constraints, the geometry of the slides illustrated in Fig. 13 and off the-shelf availability, the stiffness constant for the preload springs was determined to be 938.7 N/cm (536 lb/ in.). This spring constant was calculated, assuming a 0.32 cm (0.125 in.) initial (preload) deflection, which yields a 12.5% overall spring deflection for normal operation as well as a 19% deflection as a calculated maximum, both that are well within the range suggested by the manufacturer.

![Fig.13: Preload spring and lower wheel moment arm lengths.](Image 2725634x21070 to 4565436x26836)

The intended operation of the X-Y gantry indicates that one of the carriages is to be placed at each of the four corners of the Magnet Installation Robotic System, allowing motion along the upper pair of parallel I beams (x axis). Furthermore, a carriage is also to be placed at the bottom of each end of the upper I beams, allowing for motion along the lower I beams (y axis). From the previous, the maximum load can be calculated as the sum of the weight of the components within the Magnet Installation Unit, the four upper slide carriages, and the two parallel upper I beams. This calculation yields a value of 1776.6 N (399.4 lb) for static loading. Assuming this load to be centered within the gantry, the four lower slide carriages must then hold approximately 444.8 N (100 lb) of downward force each. Conversely, if the load was shifted to the extreme right or left, the...
two nearest lower slide carriages would bear most of the weight, or just under 889.6 N (200 lb). As the extreme case, the latter was used a design constraint for the slide carriages.

**Prototype Testing:**
In order to ensure the proper functioning of the linear slides based on rotary wheel traction, a test fixture was assembled and outfitted with the prototype Adjustable Clam Jaw Slide Assembly, as shown in Fig. 14. Several tests were performed to evaluate the possibility of jamming due to misalignment as well as smooth operation in a debris-laden environment. By misaligning a Square Rail Slide with the 7.6 × 10.2 cm (3 × 4 in.) I-beam rail, the test fixture presented in Fig. 14 forced the lower roller wheels of the Adjustable Clam Jaw Slide into the webbing of the I-beam rail. Additionally, the upper portion of the I-beam was utilized to evaluate the slides ability to operate among debris. For most other types of slides, either of these actions would immediately seize the system. The results from these tests were promising. Operation in the midst of debris such as dirt and pebbles was outstanding. Even when forced across a small rag, the operation was still normal and smooth. Pebbles and dirt were felt when encountered, but with little more than a slight vibration then a return to smooth running.

**Magnet Delivery and Insertion:**
The magnet delivery and insertion process involves a Magnet Separator (MS) and the Magnet Transfer and Insertion (MTI) end effector. The MS system (Fig.15) divides the magnets from their stored form and hands them over to the MTI end effector. The system is designed to handle two types of magnets, each of different size. One type of magnet is used in asphalt roadways and the second type is used for concrete pavements on highway structures such as bridges. The first type consists of magnets that are weaker, and will be inserted in groups of four. This group is 4 in. long and 0.87 in. in diameter.

The second type of magnets are stronger and are 1 in. long with a diameter of 1 in. These second magnets are packaged with 0.2 in. plastic cylinders that are used to keep them apart.

The magnet rows are placed into the magnet rack of the MS mechanism (shown in Fig. 15) facing the horizontal direction, and should all have the same polarity. A linear actuator applies a force to the bottom row, pushing the magnets until they hit the magnet stop.

![Fig.15: Magnet transfer and insertion system.](image)

When all the magnets of the bottom row are pushed out, the actuator moves back and lets the next stack fall to the lower level. The moving ledge in Fig. 16 supports the magnets during the transfer of magnets to the end effector. When the magnet dispenser strikes the magnet cup in the end effector, the ledge slides back, letting the magnet make contact with the cup. After contact, the magnet attaches to the steel cup due to the magnetic attraction between them.

There is an additional stop hinged on the magnet dispenser that can be brought down for use with the second type of magnets. The end effector has not only to insert the magnets into the drilled hole, but also apply the epoxy sealant. The system is designed with Floating Plates that can be seen in Fig. 17. A laser beam pointing to the drilled hole is used and an alignment cone is positioned over the hole. A pair of plates is used to ensure that the magnets would correctly go into the hole, even if the magnet cup is not directly over the hole at the time of magnet insertion. The plates support (in Fig.17) the bottom of the MTI end effector.

![Fig.14: Adjustable clam jaw slide test fixture.](image)
These plates are free to move parallel to each other while they maintain a fixed distance between them. Thus, when the alignment cone is inserted into the hole, it centers the magnet cup over the hole. Afterward, the Brake Plate closes onto the top Floating Plate with the aid of Actuator 5 (A5). Now that the Floating Plates are locked into place they will not move when the Alignment Cone is taken out of the hole. The Alignment Mechanism can correct for an alignment error of up to 0.375 in. in the horizontal plane. The top Floating Plate slides on ball transfers attached to the bottom Floating Plate. The Floating Plates are kept in contact with the use of four tension springs, pulling them together. These springs also bring the plates back to their original position once the brake is released. The end effector is integrated with the robotic system and is shown in Fig. 18. The MS mechanism is separately mounted on the trailer and can be seen in Fig. 3.

3.3 Application:
1. Magnetic markers are used to provide reference signals for the guidance and control of vehicles on the roadway in an Intelligent Transportation Systems (ITS) environment.
2. The robotic system used on asphalt type and concrete pavements type of roadways.
3. This system may be used for indoor as well as outdoor games like as athletes tracks, carraces tracks, bicycling races tracks, running competitions tracks, tennis sports court, basketball court etc.

3.4 Advantages & Disadvantages:
Advantages:
1. The mechanical design of a robotic system for automatic installation of magnetic markers on the roadway is an innovative design.
2. Magnetic markers are provides proper reference signals for the guidance and control of vehicles on the roadway in an Intelligent Transportation Systems (ITS) environment.
3. In Harsh winter environments, when weather is bad the magnetic markers controls the vehicle automatically on the roadway surface.
4. Intelligent Transportation Systems (ITS) technologies are improving safety and mobility on the nation’s highways.
5. This system has able to move above the roadway surface and reach vertically to different insertion depths.
6. A Tuned Vibration Absorber (TVA) system is used in these systems which reduce the damping & vibration during operation.
7. Structural design provides adequate strength for the drilling unit.
8. Gantry Robot system provides smooth & proper operation.
9. One advantage of magnetic markers and sensors is that they are not degraded by weather and could potentially keep the car on the road better than a human driver could during harsh weather. Magnetometers are also less affected by dirt and mud than the other systems.
10. The advantages of vehicle based systems are faster deployment and wider use. These advantages are derived from the fact that it could take years to decide which highways and corridors to build an intelligent infrastructure on.
11. It could take less time for intelligent vehicle systems to become available. Non-infrastructure dependent systems could then be used on any roads, not just those that had been upgraded.
12. This system reduces the time & men to make the roadway, which saves the capital (money).
13. The neodymium magnets used in this system are strong enough to provide the necessary magnetic field to ensure proper detection.

**Disadvantages:**

1. Installation of the magnetic markers into the roadway pavement, however, is a tedious manual operation.
2. A crew of several people is used to position a drill at the premarked location and drill a hole into the pavement.
3. The robotic system to automate this process must have the freedom to move independently in both the longitudinal and lateral directions on the roadway. It must also be equipped with control over the drilling depth.
4. Maintaining smooth contacting surfaces over the workspace of each axis of the gantry may be difficult in the harsh roadway environments.
5. During drilling operation of pavement roadway the excessive noise & vibration are produced which creates the noise pollution in the environment.
6. For operating the system required expert & trained operator.
7. These systems are costly & it reduces the human efforts due to which creates the problems for job for the men.

**FUTURE SCOPE**

One of the important considerations in the robotics system design is the presentation of the work parts of the robot. Introducing robots involves not only replacing human beings by robots but also designing a suitable working environment so that robot will be able to perform satisfactorily. This usually requires design of a suitable fixture to present the work part of robot. Many operations require several degrees of freedom of movement and some of these could be provided to the fixture. Often the fixture will be equally costly as the robot itself. Proper design of the system to present work part for operation by the end effector is very critical. In future there is further scope for improvement for to minimize or to omit the vibration, damping & noise problem comes during operation of above designed of robotics systems.

**CONCLUSIONS**

In this paper, we have presented the Mechanical Design of a gantry-type robotic system for the unique application of installing magnetic markers into the roadway pavements. Fundamentals of vibration analysis are used to design the roadway drilling subsystem that is one of the critical components of the overall robotic system.

Two innovative designs are also presented: one for achieving linear motions for the gantry axes of the robotic system without having to use linear slides and the second is a self aligning mechanism to eliminate errors in the magnet insertion task. It is hoped that the analysis and methodology presented in this paper can serve as a case study on how engineering fundamentals can be used to guide the design process as well as in enhancing the field of ITS.

**REFERENCES**