MAGNEBOTS – A MAGNETIC WHEELS BASED OVERHEAD TRANSPORTATION CONCEPT

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Abstract: This paper presents "Magnebots", a simple yet novel concept for overhead transportation. The system consists of vehicles with magnetic wheels that move on trackless ferromagnetic walls and ceilings, driven by on-board controllers and commanded by a central computer. Magnebots is designed to be a fundamentally simple technology that can fulfill many generic transportation needs including industrial material handling and positioning of overhead lights within a home, with straightforward extension to use as overhead and floor-based toys. Robust mechanical hardware, performance enhancement by controls, and vehicle coordination by wireless communication illustrate a synergistic integration of various disciplines in the true spirit of mechatronics.

1. INTRODUCTION

Automated material handling has become critical in numerous manufacturing processes because it frees up manual labor, streamlines the flow of material, allows for complexity management, reduces work in progress and improves the utilization of expensive equipment. Furthermore, there is an emerging need for clean and simple material transportation systems that can be installed in homes, offices, hospitals and other public places. A material handling technology that can meet the widespread demands from such a variety of customers must be simple, flexible, and integrable.

To address these automation needs, this paper presents the design of "Magnebots", a robotics and automation test platform under development at the MIT Precision Engineering Research Group. Magnebot vehicles move on trackless ferromagnetic walls and ceilings using magnetic wheels, driven by on-board microcontrollers and commanded by a central computer. Many existing toy vehicles employ magnetic wheels to climb walls or ceilings (Motoyuki, 1997; Ingro, 1974); however, few involve feedback control to produce desired motion. Similar industrial vehicle designs typically exhibit an unnecessary degree of complexity for the functional requirements of material handling. Furthermore, while the idea of using magnetic wheels for driving vehicles on ferromagnetic ceilings, walls and pressure vessels is well-established (Baker, 1998), it has not been employed for networks of vehicles used for material transportation.

This paper also seeks to demonstrate how a deterministic mechatronic design approach gave rise to Magnebots as a relatively simple proof of concept, without having detailed performance specifications in mind beforehand. Concurrent design of the vehicle chassis, sensor and actuator system, control algorithm, and wireless communication hardware led to a vehicle system that is robust and modular, and can be tailored to a variety of potential applications.

2. DESIGN OVERVIEW

In choosing and detailing the Magnebots system concept, the fundamental methodology of deterministic mechatronic design was invoked (Slocum, 1992). The key to deterministic design is funneling of creativity by means of continuous risk assessment, as well as systematic collection, creation and analysis of design information. Because deterministic design is based on listing facts and performing detailed analysis, simpler and more efficient designs result. Segmentation of the design problem into critical modules ensures an appropriate allocation of engineering resources throughout a project. The mechatronic approach enables a synergistic combination of mechanical engineering, electronics, control systems and computers (Craig, 2001).

Accordingly, as the first step in the design process, the functional requirements were identified:

1. A low-cost, mechanically simple vehicle design.
2. Speed and motion quality sufficient for carrying delicate payloads.
3. Expandability to large numbers of vehicles operating simultaneously in large rooms or throughout complex pathway layouts.
4. Standardized hardware and software interfaces and communication protocols.
5. Operational safety.

After a thorough analysis of needs in industrial, medical, and residential settings, the Magnebot system conceptualized in Figure 1 was selected. Specifically, a design with two magnetic wheels allows vehicles to travel up and down ramps and walls, with their payloads hanging below. Feedback control of each vehicle balances the hanging load, and vehicles can travel anywhere on the ferromagnetic panels on the ceiling and walls. Each vehicle can be connected to any payload that uses a standardized interface (SEMI, 1999). Vehicles can be stored and charged in wall-side stockers, or power can be transferred inductively. Each vehicle is a node on a self-configuring wireless network, and the vehicles communicate with each other and with a command server via standard Internet protocols. Traffic control software on the server can coordinate the vehicles so task time is minimized, utilization is maximized, and collisions are avoided.

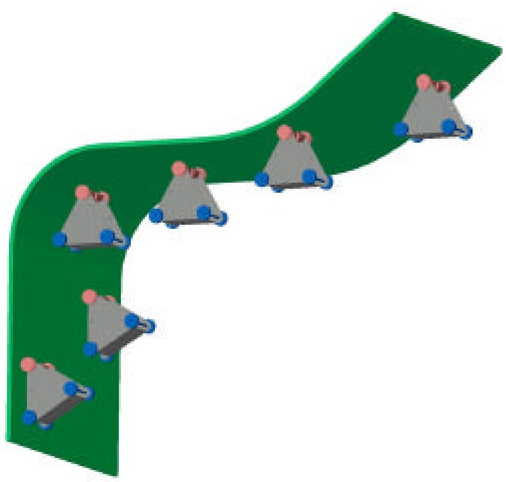

Fig. 1. Magnebots concept for automated transport, showing autonomous vehicles with magnetic wheels hanging from a ferromagnetic sheet.

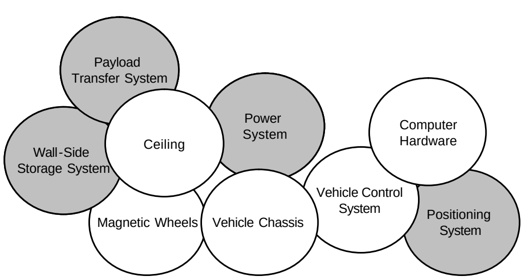

Fig 2. Critical modules of the Magnebot system. Modules currently detailed are shaded in white.

3. DETAILED SYSTEM DESIGN

Detailed design of the Magnebot system was broken into the critical modules listed in Figure 2. This section describes the ceiling, vehicle body and chassis, magnetic wheels, swing control algorithm, and communications hardware. These modules have been the initial focus of the Magnebots development. Concepts and relevant considerations for vehicle positioning and traffic management are also discussed.

3.1 Ceiling and Vehicle Design

The ceiling is designed to be modular so that it can be installed in any setting, using panels of standard size. A magnetic stainless steel (AISI 430) with high magnetic permeability and excellent formability is chosen.

The vehicle must be able to traverse horizontal, vertical, and contoured panels, eliminating the need for expensive elevators. Hence, the triangular body of Figure 3 is chosen, giving each vehicle a pair of magnetic driving wheels and two pairs of idler wheels to constrain the vehicle while traveling vertically.

Simple magnetic wheels, which can each provide up to forty pounds of magnetic force, are assembled by attaching two concentric steel discs to the sides of a Neodymium-Iron-Boron permanent disc magnet so that only the discs contact the ceiling surface. The steel discs direct the magnetic flux into the panel surface by providing a low reluctance path, thus improving the attractive force for a given magnetic strength and hence increasing the driving traction (Guy, 1972). A ring of rubber sandwiched between the two discs further increases surface traction and reduces noise arising from surface irregularities. The magnetic strength is chosen on the basis of static load carrying requirements and dynamic considerations such as impact disturbances when the wheels traverse small step discontinuities at lap joints between panels.

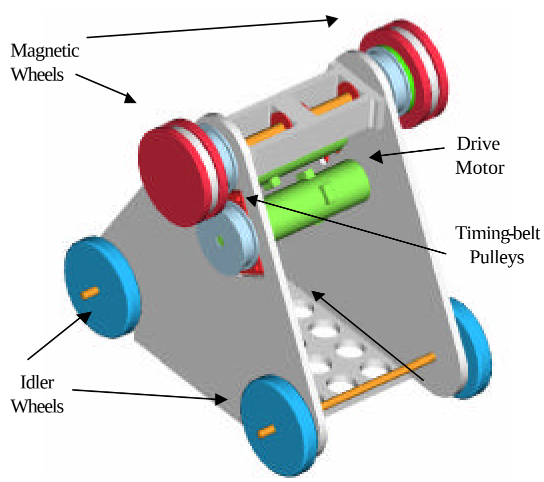

Fig. 3. Vehicle body and chassis.

The maximum drive torque for a Magnebot is required during vertical climbing. An acceleration of 0.5g demands 1.5 N-m of torque from each motor. Harmonic drive brushed DC Motors with a 50:1 gear reduction are chosen because of their compact size, high stall torque, and low backlash. The motor drive axes are offset to below the rotational axis of the wheels. Various options for transferring motion from the motor shafts to the wheels have been considered and implemented. These include a friction wheel drive, a gear drive and a timing belt drive. PWM servo-amplifiers operate the motors in current mode.

Ideally, each state that is used in feedback should be measured independently if possible. A pair of micromachined accelerometers (ADXL 202) mounted near the vehicle axle gives the pitch angle (q) measurement (Nakamura, 1996). Yaw rate (dy/dt) and pitch rate (dq/dt) are measured by a two-axis rate-gyroscope (Gyration Microgyro 100). The pitch angle measurement from the accelerometers is also used to correct the drift of the rate-gyro (Lemaire). Translation (x) and yaw (y) of the vehicle are calculated from the output signals of optical encoders integrated with the drive motors. The states of the vehicle are shown in Figure 4.

3.2 System Modeling and Control Design

Modeling and simulation of the vehicle dynamics is performed in conjunction with the vehicle design to enable appropriate choices of the sensors and actuators. Assuming that the drive wheels roll without slipping, the vehicle configuration is completely defined by three generalized coordinates: the motor angles a_1 and a_2, and the vehicle pitch angle q. A linear transformation converts these into a set of more useful system coordinates: x, the translation of vehicle axle center; y, the yaw rotation of the vehicle about the axle center; and q, the vehicle pitch angle. Inputs to the system are the torques generated by the two motors, T_1 and T_2. It is convenient to use the average forward torque and the yaw torque in the analysis:

$$T_{drive} = \frac{T_1 + T_2}{2} \;, \quad T_{yaw} = \frac{T_1 - T_2}{2} . \tag{1}$$

A Lagrangian formulation of the equations of motion followed by linearization about the equilibrium point yields the following system model:

$$\frac{q}{T_{drive}} = \frac{-a}{s^2 + k_2^{\,2}} \tag{2}$$

$$\frac{X}{T_{drive}} = \frac{b(s^2 + k_1^{\,2})}{s^2(s^2 + k_2^{\,2})} \tag{3}$$

$$\frac{y}{T_{yaw}} = \frac{c}{s^2} \tag{4}$$

The basic nature of the system transfer functions is emphasized; details of the parameters are omitted for brevity. These transfer functions are in agreement with previous models for swing dynamics of suspended loads (Ridout, 1989; Lee, 1997)

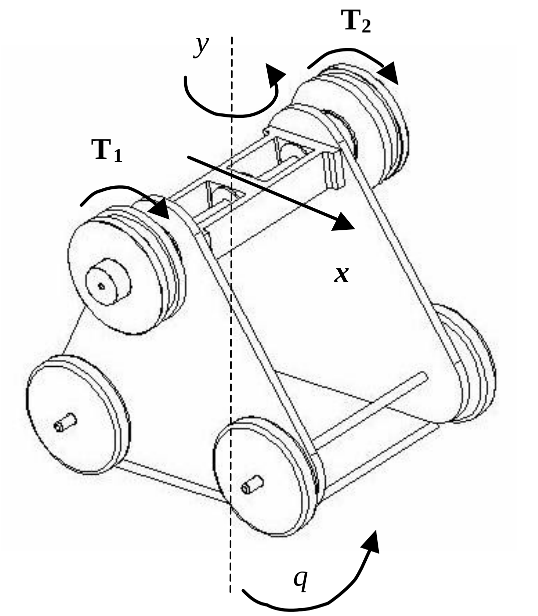

Fig. 4. Vehicle states and inputs

Frequency response and root-locus analysis tools provide qualitative insights about the dynamics and controllability of the system. A controller is initially designed assuming that the transfer functions (2) and (3) represent two independent systems. Separate compensators are used for controlling each state and the outputs of the compensators are summed. This simple control design results in moderate performance for swing control and trajectory following. Better results are obtained by implementing full state feedback.

The literature discusses extensive previous work on swing suppression of suspended loads commanded to follow a motion/velocity trajectory. Well-known strategies include command shaping, loop within loop, time optimal control, and full-state feedback (Lee; Ohnishi, 1989, Ridout). Experiments that implement these and other ideas to achieve high performance motion control of the Magnebot vehicle are underway.

Initial implementation and testing of the controller designs is conducted using d-Space, a real-time controls prototyping tool. A full-state feedback algorithm designed in Simulink, which seamlessly operates with the d-Space hardware, is presented in Figure 4. When controlled using d-Space, the vehicle is connected to a desktop PC by an umbilical cord. Once the controller has been satisfactorily tuned, the logic is transferred to a microprocessor (RabbitCore 2200) on the vehicle. Sensor signal connections on the prototype vehicle are modular, so that the vehicle inputs and outputs can be easily switched from the d-Space controller to the microprocessor board.

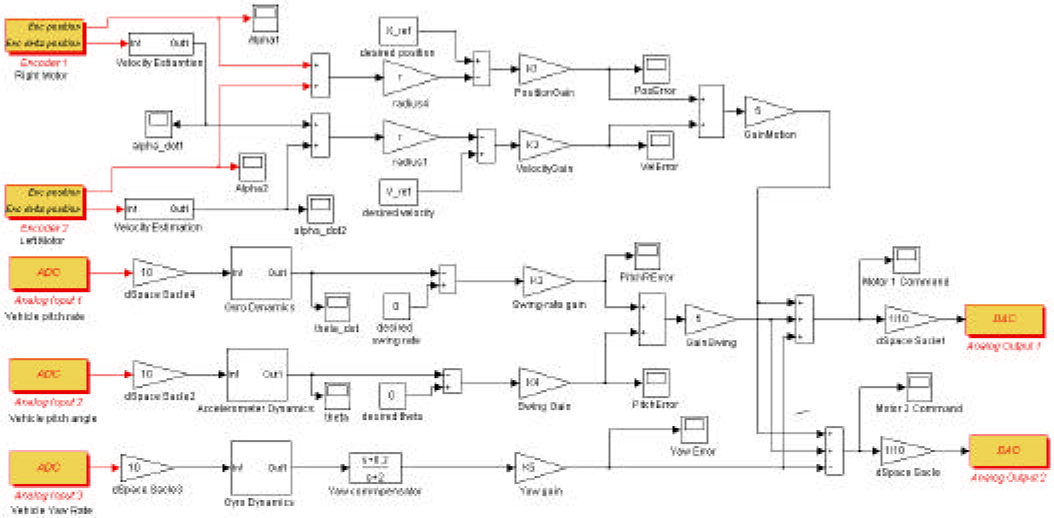

Fig. 4. Full-state feedback algorithm for swing control.

3.4 Communications Hardware

To facilitate path planning and traffic control, each vehicle is capable of wireless packet-data communication with other vehicles and a central control server. As shown in Figure 5, the on-board microprocessor to which the sensors are connected, communicates externally via a wireless gateway (e.g. Ethernet-to-802.11b or Bluetooth chipset). Because each vehicle is assigned a unique network address, addition of new vehicles to the system and reliable communication among large numbers of vehicles, are straightforward procedures.

Communication is established from the central computer to a vehicle by opening a socket to the vehicle's network (IP) address, and sending standard input and output commands to the memory command addresses of the sensors and actuators. In the future, the central computer interface would present a real-time map of the vehicles, inventory data from each vehicle, and means for issuing commands (e.g. pick-up or drop-off at a desired handling station) to individual vehicles or groups of vehicles.

3.5 Positioning and Tracking

The system must incorporate a simple method of determining the position of each vehicle with respect to the panel space. This is conceptualized as a number of position references that can be read by the vehicle's on-board electronics, placed on each panel or near the seams between adjacent panels. The position references could be 1-dimensional or 2-dimensional black-and-white bar codes, with the vehicle having a photodetector facing the ceiling at a small distance from the metal surface. If the bar code is 1-dimensional, it gives the numbers of the adjacent panels and the relative position of the vehicle from the edges of the panels. If it is 2-dimensional, the interpreted pattern is dependent on the angle of reading; hence it is possible to estimate the orientation of the vehicle with respect to the panel intersection. As shown in Figure 6, the numbers of the panels give the vehicle's x-coordinate, while the bar code's unique number gives the y position. Wireless radio frequency identification (RFID) tags could be used instead of bar codes.

Signals from the on-board accelerometers, encoders, and gyroscopes are used to interrogate ("dead-reckon") the vehicle's position while away from the references (Lemaire). When the position estimated by dead-reckoning differs from the reference reading and exceeds the error tolerance of the desired trajectory, a correction is applied to the control signals. More accurate referencing can be achieved by mechanical homing, where the centroidal position of the load interface (e.g. a kinematic coupling) triggers an absolute position reset. Low-cost methods of three-dimensional local positioning (Priyantha, 2000) are also being investigated.

3.6 Traffic Management

Since the vehicles are free to move all over the ceiling, path interference detection and collision avoidance are crucial. Traffic can be managed by a central computer that commands all the vehicles, computing each vehicle's position. In addition, proximity sensors on each vehicle can activate emergency stops or obstacle avoidance maneuvers using simple logic in the microcontroller program.

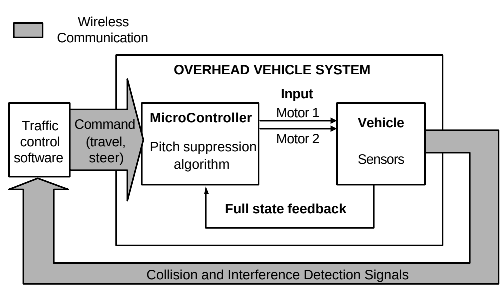

Fig. 5. Information flow for local control with centralized command and monitoring.

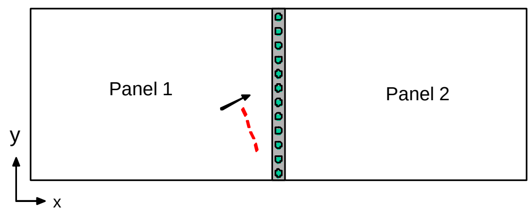

Fig. 6. Local reference positioning using barcodes.

An alternative traffic management strategy would be based on distributed controls, where the communication between nearby units is peer-to-peer and each unit has decision-making authority. As the number of vehicles increases, distributed controls become more promising because of reliance on quantities of data limited by the region of control influence. In either case, the vehicles have to follow a 'cooperative motion' strategy, so as to produce the maximum transportation efficiency without colliding. Significant research addresses distributed controls; work of Alur (2000) and others will be a useful reference for development. In an industrial application, the vehicle traffic control software can be designed to work with a Computer Integrated Manufacturing (CIM) system, which seeks to optimize operation of a factory at a higher level.

4. APPLICATION: AUTOMATED MATERIAL HANDLING IN HOSPITALS

The Magnebot system is well-suited for automated material handling in hospitals, involving transport of delicate medical samples, supplies, equipment, and documents. As hospitals look to improve operational efficiency and minimize human error, automated handling can free valuable manual labor, streamline material flow, allow for complexity management, conserve space and improve equipment utilization. Furthermore, future operation theatres, such as the "Operating Room of the Future" currently under construction at Massachusetts General Hospital, must be equipped with machines and lighting that can be reconfigured under computer control, and with means for expedient transportation of samples, supplies and instruments to other parts of the hospital.

Fig. 7: Demonstration Magnebot space in CIMIT simulation room: (a) L-shaped ceiling section; (b) Curved transition to vertical wall section.

In collaboration with the Center for Integration of Medicine and Innovative Technology (CIMIT), a simple demonstration Magnebot system has been installed in a medical simulation room in Cambridge, MA. Shown in Figure 7, the demonstration ceiling consists of an L-shaped overhead roadway and a single vertical wall section bridged to the ceiling by a 90^o curved panel. The panels are 1/16" 430 stainless steel, anchored 12' above the floor to a steel U-channel support grid.

For the first system demonstration in October 2001, the vehicles shown in Figure 8 were driven manually via Futaba radio-control handsets. Subsequent development produced the vehicle shown in Figure 9. The triangular aluminum body is approximately 8" high, with 3" diameter wheels. The magnetic wheels, consisting of stainless steel washers surrounding neodymium iron boron magnets, are driven by 24V harmonic drive DC motors. The maximum driving torque at 100 RPM output is easily sufficient to accelerate the 14 lb. vehicle vertically up a wall. The motors are connected through power amplifiers to a 24V lithium-polymer battery pack. The swing control algorithm, developed and tested using d-Space and Simulink, is executed using a 22 MHz microprocessor with external amplifiers to drive the motors. The microcontroller board has an Ethernet interface, which is connected to a Lucent 802.11 wireless LAN converter. This enables the vehicle to be commanded over TCP/IP using a simple Java window interface running on a laptop computer.

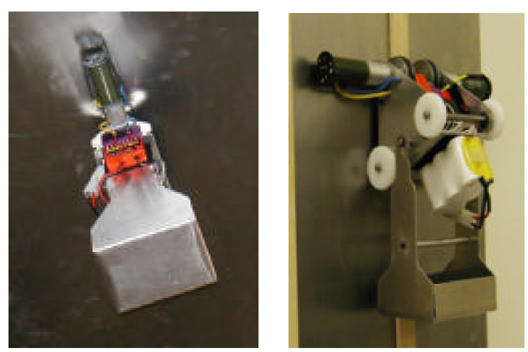

Fig. 8: First prototype Magnebots: (a) Two-wheel pendulum design hanging from ceiling; (b) Triangular vehicle with detachable basket, climbing wall.

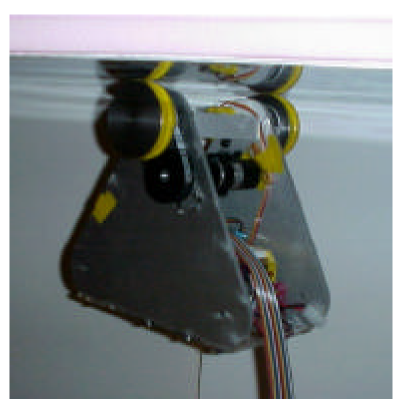

Fig. 9: Vehicle with on-board microcontroller executing swing suppression algorithm.

With the Magnebot system installed in a hospital, one should be able to place a sample in a holding bin at a wall-side loading station, for example in an operating room. Then one would issue a command indicating the destination and task priority, for example by pressing a button at the load station, by voice, or by command to a graphical interface on a computer terminal. A vehicle would come to the loading station, retrieve the sample, and take it to the destination. Based on the task priority and the task optimization algorithm, the vehicle may make additional pickup or drop-off stops before reaching the destination of the sample. With a standard interface for coupling the vehicle to the payload carrier, different payload carriers can be designed for different payload types, while the vehicle body and load stations would be identical. The same interface could be placed on equipment such as lights, power supplies, and drug delivery devices to be positioned overhead.

The transportation system shall also be capable of identifying samples at load stations, while in transit, and at destinations. Rule-based methods of sample-vehicle, sample-destination, sample-physician, and sample-patient verification and authentication are possible. These consistency checks can reduce human errors. Identification can be achieved by placing an RFID tag on each sample, vehicle, load station, and so on. A reader on each vehicle and at each station would transmit the payload data to a central database for storage and distributed access.

5. CONCLUSION

The Magnebot concept allows for an immense degree of flexibility and expandability in material transportation using autonomous robotic vehicles. The system does not consume valuable floor space. Furthermore, expansion of the system is straightforward by adding additional steel sections as flat panels or easily formed curved sections, and by registering new vehicles to the information system. Magnebots could be used in factories, homes, libraries, hospitals, restaurants, and stores—conceivably anyplace where an inexpensive and flexible system of small mechanized vehicles is needed.

The test system for hospital material handling in collaboration with CIMIT is being used as an 'open technology' platform to channel the resources and creativity of various medical, industrial and academic groups towards a common objective. This facilitates a systematic and concurrent development of automation standards and simulation models along with the necessary hardware and software technology, all of which are essential elements of a successful automation strategy. Development of the vehicle control algorithm, wireless communications hardware, and a simple local positioning system will continue, with hope of demonstrating task-commanded material handling at CIMIT within the next year. Elementary cooperative motion and traffic control algorithms among small numbers of vehicles will also be tested.

More detailed information about the Magnebots project is at http://pergatory.mit.edu/magnebots.

ACKNOWLEDGEMENT

This research was funded by CIMIT, Center for Integration of Medicine and Innovative Technology. The authors would like to thank Alexis Weber, Sara Cinnamon, Sean Montgomery, Abraham Schneider and Kabir Mukaddam for their help. John Hart gratefully acknowledges the fellowship support of the National Science Foundation and the Fannie and John Hertz Foundation.

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