1

Introduction

1.1 Wheels and bearings

The wheel is without doubt one of man's most impressive early inventions. The important difference between a wheeled cart and its predecessor, a sledge, lies in the arrangement and quality of the bearing surfaces. The Concise Oxford English Dictionary defines a bearing as: 'a carrier or support for moving parts of any machine; any part of the machine that bears the friction'. Even a crude wheeled cart has relatively smooth and small bearing surfaces whereas a sledge has much larger bearings, one of which (the ground) can be quite rough. The linear motion bearing between the sledge and the ground, was thus transformed through the use of wheels, to a rotary bearing between two controlled surfaces.

For the majority of applications the advantages of the mechanical transformation from linear to rotary bearings have stood the test of time well. However, by harnessing magnetic forces to support a moving body, a bearing with no physical contact between its surfaces is possible. The lack of physical contact offers superior performance over mechanical bearings in terms of friction and wear. For certain wheel-on-rail transport applications, the benefits can be even greater, since magnetic linear bearings can be used to replace both the wheel and its rotary bearing. For such applications, the wheel may in future become as unusual as a horse-drawn carriage is today.

There are a number of different electromagnetic methods for supporting moving or rotating masses[1] (see Table 1.1). The attraction schemes are conventionally referred to as electromagnetic suspension (EMS), whilst repulsion schemes are referred to as electrodynamic levitation (EDL). A comprehensive review of the various EDL and EMS schemes and their development potential can be found in reviews by Jayawant,[2] Sinha[3] and Weh.[4] This dissertation describes the development of new, improved techniques for controlling d.c. electromagnets for vehicle suspension applications.

Table 1.1 Electromagnetic methods of supporting moving or rotating masses

Levitation using:
- forces of repulsion between permanent magnets.
- forces of repulsion between diamagnetic materials.
- superconducting magnets.
- forces of repulsion due to eddy currents induced in a conducting surface or body.
- force which acts on a current-carrying conductor in a magnetic field.
- mixed μ system, where μ is the permeability of the material.

Suspension using:
- a tuned LCR circuit and the magnetic force of attraction between an electromagnet and a ferromagnetic body.
- controlled d.c. electromagnets and the force of attraction between magnetised bodies.

1.2 Controlled d.c. electromagnetic suspension

The force of attraction between two magnetised bodies is proportional to the inverse square power of their separation, thus there is no point of equilibrium between two magnetised bodies (Earnshaw's theorem[5]). The force between an electromagnet and its reaction rail is therefore open-loop unstable and closed-loop feedback control of the electromagnet is necessary to stabilise the force and provide a satisfactory suspension response. The essential elements of an EMS system, therefore, consist of an electromagnet and its ferromagnetic reaction rail (see Figure 1.1), feedback sensor(s) and associated control algorithm processing, and finally a current controller for the electromagnet.

Graeminger appears to have been the first to propose a controlled electromagnetic attraction system[6] in 1912. He proposed a U-shaped electromagnet suspended beneath an iron rail to carry letters. A measure of the air gap between the electromagnet and the track was coupled mechanically to a rheostat which varied the electromagnet coil current.

Twenty-five years later, Kemper built the first prototype EMS[7] which supported 210 kg at an air gap of 15 mm with a power consumption of 270 W. A capacitive displacement sensor was used to measure the air gap. Thermionic valves were used to amplify the air gap signal and a velocity signal, and also to drive the electromagnet coil.

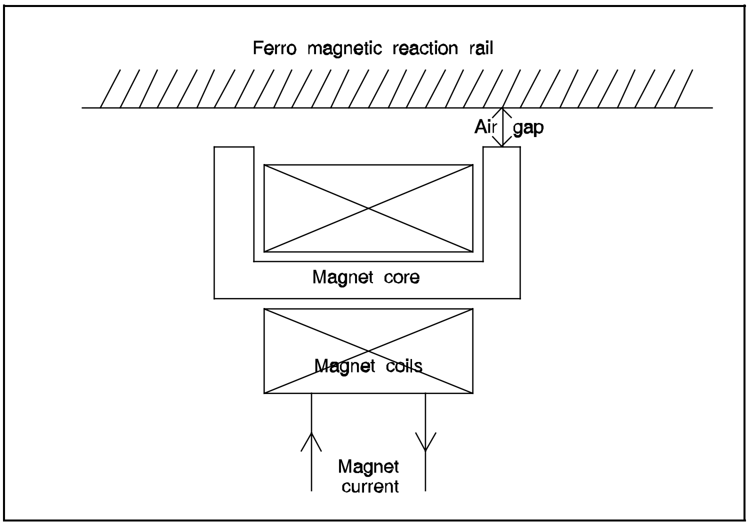

Figure 1.1 Configuration of electromagnet and reaction rail

However, the weight of the thermionic valve power controllers used to implement Kemper's EMS precluded their use in transport applications. It was after 1970, with the advent of transistor technology capable of handling suitably high power levels, that research into the use of EMS for transport applications flourished. Before reviewing the more significant developments in vehicular EMS systems, it is instructive to consider the configuration of the functional components of a conventional train suspension.

1.3 Vehicle suspension configuration

Conventional trains are supported by a primary suspension which is coupled via a secondary suspension to the vehicle chassis. The function of the primary suspension (typically stiffly sprung wheels), is to maintain contact with the track, and hence avoid derailment. The function of the secondary suspension is to provide a low bandwidth coupling between the primary suspension and the vehicle, thus decoupling the vehicle from high frequency track irregularities. The secondary suspension employs suitable stiffness and damping components so that an acceptable passenger ride quality is maintained for a given train speed and track profile. The secondary suspension also reduces the wear and tear on the track and the primary and secondary suspensions. This is because the decoupling of the vehicle mass from the wheels reduces the dynamic forces generated by track irregularities.

The two essential elements of a conventional train suspension are therefore the primary suspension, which can be viewed as a high bandwidth track follower, and the secondary suspension, which acts as a low pass filter with a low bandwidth.

Kemper's approach of using air gap clearance and velocity feedback provides the electrical equivalent of mechanical stiffness and damping respectively. The controlled electromagnet, therefore, behaves in a similar manner to a conventional suspension with the stiffness determined by the sum of the air gap feedback gain and the negative electromagnet stiffness, and the damping is determined by the velocity feedback gain.

In principle, a conventional secondary suspension design could be utilised, but with an electromagnet replacing the wheel. The feedback gains of the electromagnet controller are designed to give the appropriate primary suspension stiffness and damping.

Alternatively, the electromagnet could be used to replace the secondary suspension by setting the feedback gains to give the stiffness and damping required for the secondary suspension. A primary suspension is not required in this case due to the lack of physical contact between the secondary suspension and the rail. This arrangement eliminates all moving parts and associated maintenance requirements from the vehicle suspension, plus all of the size and weight associated with wheels, axles, bogies, springs and dampers. Whether this trade of a mechanical for an electromagnetic systems pays off obviously depends on the cost, weight, size and maintenance requirements of the electromagnet and its associated control circuitry. In addition, Hrovat[8] has shown that reducing a vehicle's unsprung weight (that of the primary suspension) enables the ride quality to be improved. Since an EMS incorporating both primary and secondary suspension would have no unsprung weight, ride comfort quality above that of mechanical suspensions is theoretically possible.

The two basic suspension configurations for EMS systems are therefore electromagnetic primary with conventional secondary suspension, or electromagnetic primary plus secondary suspension, the latter scheme offering a suspension with no moving parts.

1.4 Review of electromagnetically suspended vehicles

Table 1.2 lists some of the milestones in the development of electromagnetic vehicle suspensions. The first vehicles developed incorporated both primary and secondary suspension in the EMS. Subsequently however, the high speed systems and some low speed systems have reverted to using conventional secondary suspensions.

Table 1.2 Electromagnetically suspended vehicles

Organisation	Vehicle	Date	Weight /t	Speed /kph	CSS	Propulsion
MBB, FRG	Magnetmobil	1971	7	90	x	DLIM
Krauss-Maffei, FRG	Transrapid-02	1972	11	165	x	LIM
Rohr Industries, USA	Romag IMPS	1972	1	low	x	LIM *
University of Sussex, UK	Sussex 1t	1974	1	low	x	LIM
Japan Airlines, Japan	HSST-01	1975	1	300	x	LIM
British Rail, UK	BR 3t	1976	3	low	x	LIM
Transrapid Consort.,FRG	Transrapid-06	1981	122	400	✓	LSM *
PMG Consortium, UK	PMG 8t	1984	8	48	x	LIM
Timisoara Poly., ROM	Magnibus-01	1988	4	72	✓	LIM *
HSST Consortium, Japan	HSST-05	1989	-	200	✓	LIM

Key: CSS - Conventional Secondary Suspension
DLIM - Double-sided Linear Induction Motor
LIM - Single-sided Linear Induction Motor
LSM - Linear Synchronous Motor
* - Suspension is combined with propulsion system

The Magnetmobil[9] was the first full-scale system capable of carrying passengers. It used a pair of orthogonally orientated electromagnets at each corner to provide independent lift and lateral suspension. Propulsion was provided by a double sided, short stator linear induction motor mounted on the vehicle, with an aluminium reaction rail on the guideway. The Transrapid-02[10] vehicle, used two in-line electromagnets at each corner which were slightly offset either side of the rail. Both electromagnets contributed lift force, but a lateral force component was also generated by adjusting the relative drive levels between the electromagnet pair. The propulsion configuration was the same as the Magnetmobil except for the use of a single-sided linear induction motor. The Romag system[11] took a different approach, using one linear induction motor at each corner to provide combined lift and propulsion, but there was no active control of lateral motion. The University of Sussex[12] vehicle, the BR[13] and PMG[14] vehicles and the HSST-01[15] used essentially the same configuration as the

Transrapid-02, incorporating the Krauss-Maffei offset electromagnet arrangement for lateral guidance.

For practical reasons, the nominal operational air gap of EMS systems is limited to about 15-20 mm, above which the weight and power consumption of the electromagnets become excessive.[16] For high speed systems, meeting ride comfort requirements with such a small allowable air gap deviation would require excessively expensive track construction and alignment maintenance. As a consequence, practical high speed EMS systems need to use an electromagnetic primary suspension with a conventional secondary suspension capable of a much larger suspension deflection.[17]

The Transrapid-06[18,19] system uses a continuous array of ‘magnetic wheels’ down the full length of both sides of each coach. Each magnetic wheel is coupled to the coach via an air-spring secondary suspension and operates autonomously offering a highly modular system with significant redundancy and hence robustness to individual module failure. The lift and propulsion are both provided by a long stator (active track) linear synchronous motor.[20] The lift force is controlled by varying the effective resistance of coils on the lift/propulsion ‘rotor’. Lateral guidance is provided independently of lift/propulsion in each magnetic wheel by controlled d.c. electromagnets mounted orthogonally with respect to the lift units. The problem of non-contacting power collection for propulsion at high speed was overcome through the use of an active track. The power required for the onboard controllers and general vehicle services is provided by linear synchronous generators which are incorporated into each lift/propulsion unit. All other vehicles use power rails with sliding shoes for power collection. The Magnibus-01[21], a low speed system, appears to be functionally equivalent to the Romag system, but with the addition of conventional secondary suspension. The HSST-05[22,23] system is the latest development of the HSST-01 and now employs a conventional mechanical secondary suspension.

In addition to passenger transport applications, EMS based materials transportation systems for use in automated factory production lines have been researched in Japan.[24,25] These systems typically use a small vehicle weighing about 10 kg to carry a load of just over 10 kg. Propulsion is provided by a number of short stator linear induction motors distributed suitably along the guideway with an aluminium reaction plate mounted on the vehicle. Such systems use onboard battery power with special recharging stations to reduce power collection problems. To maximise the operational time between recharges, hybrid magnets are used consisting of permanent magnets plus control coils. The suspension controllers are designed to operate the hybrid magnets at an air gap which requires zero average current rather than at some fixed nominal air gap.

Maximising the benefits of the non-contacting nature of electromagnetic suspension requires the other vehicle systems to use a non-contacting technique. Whilst linear induction or synchronous motors provide an appropriate propulsion technique, power collection and route switching remain practical problems. Power collection from an active track as employed by the Transrapid system is likely to prove too expensive for low speed applications. Route switching is also a problem because a gap must be introduced into a suspension rail at a junction to allow an electromagnet plus its support structure to cross the rail. The suspension force is therefore lost as the electromagnet traverses the rail gap. This problem can be overcome by using a duplicate set of electromagnets with a suitable arrangement of duplicate rails at the junction. However, such a solution is undesirable due to the resulting poor suspension utilisation and the increase in weight. A novel solution was proposed by Jayawant and Wheeler[26] where two sets of magnet pole faces were connected to a single electromagnet, but this still incurred a significant weight penalty over conventional electromagnets. An acceptable configuration for low cost, non-contacting power collection, and route switching without track movement or contact has yet to be established.

Having reviewed the general configuration of some representative electromagnetically suspended vehicles, the detailed structure of an electromagnetic vehicle suspension system is examined next.

1.5 Anatomy of an electromagnetic vehicle suspension

The anatomy of an electromagnetic vehicle suspension is largely determined by the functional requirements of the suspension system. The main functional requirement is to decouple the passengers from guideway irregularities whilst following the general guideway profile. In addition, external disturbance forces such as wind gusts must be resisted, and passenger load variations must be accommodated. The forces generated by the electromagnets suspending an EMS vehicle must therefore be controlled to meet these requirements. The suspension parameters depend on factors such as guideway profile, guideway stiffness and natural frequency, operational air gap range, disturbance forces, passenger load variations and the required level of passenger comfort.

An electromagnetic vehicle suspension consists of three important components. Firstly, a set of electromagnets is required to provide force actuation to the vehicle body. Secondly, a technique for decoupling the electromagnet motions is required, and finally, suspension control algorithms are required for each of the decoupled motions. Each of these components will now be considered.

1.5.1 Suspension force actuation

The number and configuration of the electromagnets required to suspend and guide a vehicle depends mainly on the number of degrees of freedom to be controlled. Practical factors such as vehicle shape and the required electromagnet redundancy (needed to provide system availability under partial failure conditions) also contribute to the vehicle configuration.

A vehicle assumed to behave like a perfectly rigid body in free space is capable of linear motion and rotation with respect to three orthogonal axes. Convenient horizontal reference axes for a tracked vehicle are the longitudinal and lateral axes of the guideway, with the third orthogonal axis being vertical. The linear motion of the vehicle along the guideway is controlled by the propulsion system, thus leaving five degrees of freedom to be controlled by the vehicle suspension system. The vehicle mode motions, which are conventionally referred to as heave and sway (vertical and lateral motions), and pitch, roll and yaw (lateral, longitudinal and vertical axis rotations), are illustrated in Figure 1.2.

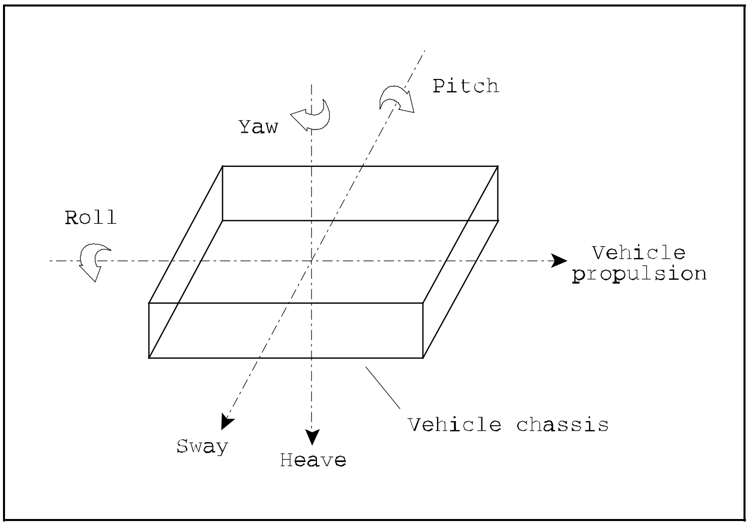

Figure 1.2 Vehicle mode motions

In reality, vehicle bodies are not perfectly rigid, and so additional degrees of freedom exist. These correspond to the various linear and torsional bending motions which can occur due to vehicle flexibility. Complete and independent control of the motion of a vehicle body thus requires five independent electromagnet actuators for the rigid body motions, with additional actuators needed if control of vehicle bending is required.

For practical reasons, most EMS vehicles have used eight electromagnets, with two located at each corner of the vehicle to provide lift and lateral forces. Due to redundancy in the configuration, the four lateral forces produce only two independent vehicle mode forces/torques, namely sway and yaw. The four lift forces produce four independent vehicle mode forces/torques, namely heave, pitch, roll and torsion (vehicle body twist axial to its length).

1.5.2 Decoupling the electromagnet motions

The simplest vehicle suspension control strategy would be to use independent suspension controllers, with identical parameters for each electromagnet. With this lift control configuration, the resulting heave, pitch, roll and torsion motions of the vehicle would all experience the same controller parameters. Unfortunately, for a vehicle with electromagnets mounted directly on the chassis, the resultant stiff coupling between the electromagnets results in the independent control configuration being generally unacceptable. This is because the high controller stiffness and zero steady-state air gap error required for the vehicle heave mode also applies to the other vehicle modes. When zero torsion error cannot be achieved, for example due to normal track/vehicle misalignment, the vehicle would be largely supported by a diagonal pair of electromagnets, with the other electromagnet pair sitting virtually idle. This poor load force distribution would cause two of the electromagnets to be overloaded. Independent lateral electromagnet control would also produce equal suspension parameters for the yaw and sway motions. This may be acceptable since the lateral motions are largely decoupled. For general ride comfort considerations, it may also be desirable to have different settings for the heave, pitch and roll mode suspension controllers.

If a conventional secondary suspension is used to couple the electromagnets to the vehicle, then the low stiffness of the secondary suspension largely decouples the high stiffness primary suspension electromagnets from the vehicle and hence from each other. In this case, the electromagnets can be controlled independently, and autonomous ‘magnetic wheel’ modules can be employed as exemplified by the Transrapid-06 vehicle. The ride comfort characteristics of the vehicle's heave, pitch, roll, sway and yaw motions are then determined by the conventional secondary suspension.

For vehicles employing electromagnets for secondary suspension, the direct attachment of the electromagnets to the vehicle chassis results in a tightly coupled, multivariable system. In this case, the independent electromagnet control scheme is unacceptable for the reasons given earlier. A multivariable controller is therefore required which must decouple the electromagnet motions (eg. by transforming them to independent vehicle motions) and apply independent suspension controllers to each decoupled mode.

Multivariable control of the vehicle system is complicated due to the nonlinear and unstable nature of the electromagnet force characteristic. As a consequence, all of the vehicles listed in Table 1.2 that employed electromagnets for secondary suspension used independent electromagnet force stabilisation controllers. The controllers significantly reduced the force instability by using feedback of the derivative of the air gap flux for each electromagnet. The multivariable control schemes used linear decoupling to transform between the electromagnet motions and the vehicle mode motions. Independent suspension controllers were then applied to each vehicle mode motion. Results from Sinha and Jayawant[27] showed that the multivariable control scheme could achieve a superior control performance relative to an independent electromagnet suspension control scheme. However, the nonlinear electromagnet force characteristic resulted in these schemes suffering from significant cross-coupling between the heave, pitch, roll and torsion modes which impaired the dynamic response of the vehicle suspension. In addition, the elimination of steady-state pitch and roll offsets through the use of error-integral feedback action could not be achieved on the Sussex and PMG vehicles. This was due to low frequency cross-coupling problems between the vehicle heave, pitch and roll modes.

1.5.3 Control of the vehicle mode motions

Having examined the configuration of the vehicle suspension control system, the independent vehicle mode controllers that are applied to the decoupled motions can now be considered. It is these controllers that must achieve the main functional requirements of the vehicle suspension system outlined earlier.

The early EMS vehicles used air gap feedback to provide stiffness relative to the rail and absolute velocity feedback to provide damping. The stiffness had to be high in order to counter load variations and disturbance forces within the small available operational air gap range. The high stiffness resulted in a suspension bandwidth of around 6 Hz, which was too high to meet ride comfort specifications for a cost effective guideway. The PMG vehicle overcame this problem by using air gap stiffness at low frequencies (below about 1.5 Hz), with vehicle position stiffness used for higher frequencies. This was achieved through the use of a complementary pair of low and high pass filters on the air gap and position feedback signals respectively. The suspension thus provided a low frequency coupling to the guideway with a high absolute stiffness to load variations and disturbance forces. Damping was provided by applying phase-lead compensation to the complementary stiffness signal. The absolute velocity and position signals were obtained by integration and double integration respectively of the output from an accelerometer mounted near each electromagnet. The integrators were given a low frequency cutoff to prevent drift problems. Acceleration feedback was also employed in an attempt to reduce the nonlinearity of the multivariable system.

For a guideway without gradients, a simple two pole filter design was satisfactory for the complementary filters. However, the gradient entry and exit characteristic required for the PMG guideway caused unacceptable air gap deviations when using two pole filters. The final design used two and three pole filters to provide a compromise between ride comfort and air gap deviation at guideway gradients.

The parameters of the vehicle guideway can have a critical influence on the steady-state and dynamic behaviour of the vehicle suspension due to the coupling between the vehicle and the guideway. If the static deflection of the guideway due to the weight of the vehicle is to be accommodated without disturbing the passengers, then the guideway deflection must be less than the operational range of the secondary suspension. For vehicles with an electromagnetic secondary suspension, the small operational air gap range requires a much stiffer guideway than that required for vehicles employing a conventional secondary suspension. The high guideway stiffness generally simplifies suspension design by enabling the track to be assumed to be rigid. However, to avoid resonant oscillations, an adequate margin between the natural frequencies of the various system components must be ensured. For example, the stiff track required on the elevated concrete guideway for the PMG vehicle was required to have a natural frequency above 10 Hz, to give adequate separation from the suspension-guideway coupling bandwidth of about 1.5 Hz and the force rejection bandwidth of about 6 Hz.

1.6 Proposed vehicle suspension control strategy

The objective of the research described in this dissertation is to improve the performance of electromagnetic secondary suspension for vehicles through the use of improved control techniques.

The design of the electromagnetic suspension scheme for the PMG vehicle is the most sophisticated of those employed for electromagnetic secondary suspension. However, it has two areas of weakness. The first weakness is due to the nonlinear electromagnet force actuation which causes cross-coupling between the independent vehicle mode motions. This impairs the dynamic response of the suspension and prevents the use of self-levelling roll and pitch mode controllers. The inaccurate nominal air gaps which result from the lack of a self-levelling response reduce the allowable air gap deviation, and hence give poor electromagnet utilisation.

To overcome this problem, a novel force control algorithm is proposed which is capable of providing a sufficiently linear and stable force actuation. First, a detailed nonlinear model of the electromagnet force characteristic is developed. The proposed control algorithm then employs the model to determine the appropriate electromagnet excitation for any required operating point.

The second weakness of the PMG vehicle is structural and stems from the use of a single control block for the vehicle mode controllers. This enables the disturbance force rejection characteristic to be freely chosen, but the guideway coupling for flat guideways and guideways with gradients are both determined by the air gap feedback filter. The implementation of the guideway interaction functions is thus tightly coupled and the resultant performance of guideway following is therefore compromised. For example, it may be possible to improve the vehicle guidance at the entry and exit of curves by employing a matched filter technique. The matched filter could use the functions defining the guideway curves to actively identify curves and guide the vehicle appropriately.

The proposed solution to this structural problem is to partition the vehicle mode control algorithm into two independent blocks. The first block is fed with the guideway position which it processes using a suitable guideway following algorithm to produce a vehicle position demand. This is then fed as the reference into a vehicle position control algorithm which employs position error integral feedback to eliminate steady-state position errors, and high stiffness in order to resist load variations and disturbance forces. The force demands from the vehicle position controller are then sent to the electromagnet force controllers. Figure 1.3 outlines the structure of the proposed vehicle control scheme.

If active guideway damping is also required,[28] then assuming linear superposition, the proposed system could be augmented with another independent control block. This would receive the guideway velocity and, using a suitable algorithm, determine the required damping force demand to be added to the force demands from the vehicle position controller. Such a configuration would require a detailed analysis of the coupling between the various control blocks since linear superposition of the vehicle position control action and the track damping action is likely to be impaired by nonlinearities within the vehicle suspension and guideway.

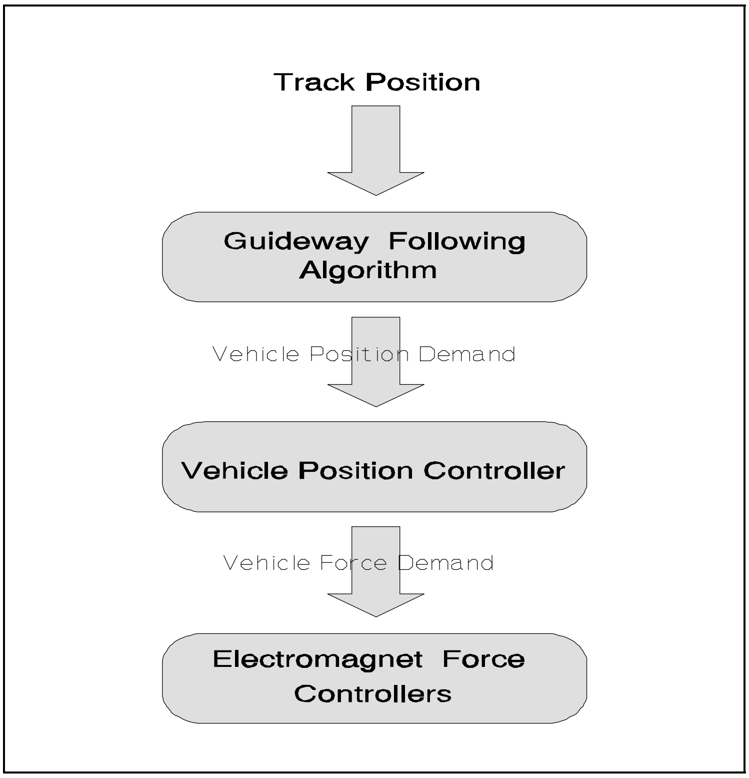

Figure 1.3 Structure of the proposed vehicle control system

Having outlined the structure of the proposed vehicle control strategy, the design must be developed and validated. For the vehicle suspension system, the features which are difficult to model accurately are critical to the performance of the overall system. The modelling difficulties are attributed to effects such as the nonlinearity and higher order characteristics of the electromagnets, the vehicle chassis and the track. Proof of concept using simulation as a validation tool is therefore considered to be inappropriate for the vehicle suspension system. The development of an experimental system (using simulation as a design tool) is therefore considered to be necessary to facilitate validation of the proposed vehicle control strategy.

1.7 Proposed implementation strategy

Three principle options are available for the hardware implementation of the suspension controller for the experimental vehicle. These options are, analogue electronic circuitry, programmable digital processors, or a combination of both analogue and digital hardware. In order to determine the best implementation strategy, each of the control system components must be considered.

For the electromagnet force control algorithm, analogue electronic circuitry is impractical due to the complexity of the nonlinear electromagnet model which is embodied within the algorithm. The use of a programmable digital processor is therefore required for the force controller. The vehicle mode decoupling algorithms and mode position controllers are linear and can thus be readily implemented using either analogue or digital techniques. For the final control system component, the guideway following algorithm, a programmable processor implementation is required to ensure maximum flexibility in the choice of algorithm. In addition to the signal processing requirements of the control system, executive control of the vehicle in terms of startup, shutdown, fault detection and data monitoring is needed, and this is more readily and flexibly achieved through the use of a programmable controller. The only system functions that could feasibly use analogue signal processing are the vehicle mode decoupling and the vehicle mode position control. Since these functions are logically located between components that need digital signal processing, additional analogue/digital conversions would be required if analogue signal processing were employed. Therefore, to simplify the system hardware configuration, eliminate the problems of drift and offsets, and maximise the flexibility of the implementation, the use of digital processing for all system functions is proposed.

Since the control algorithms for the electromagnet forces and the vehicle mode motions are independent of each other, they can be readily implemented using a coarsely grained parallel processing[29] approach. The prime benefit of this approach is that the vehicle signal processing can be performed by a number of low cost microprocessors. Additional benefits include easily scalable electromagnet configurations, and the possibility of achieving fault tolerance at low cost through the use of spare processors.

The main disadvantage of a parallel processing approach is due to the overhead associated with the provision and use of the required inter-processor communication.

Overall, the benefits of parallel processing are considered to outweigh the disadvantages for this particular application. The proposed implementation strategy can use one processor per electromagnet force controller and vehicle mode motion controller. One processor can conveniently run both of these functions because only one is active at any instant in time.

The microprocessor family selected to implement the parallel processor control system was the Inmos transputer.[30] This was chosen because it provides a range of processor powers, parallel language support using occam, a parallel processor development system, a low cost/performance ratio, and also because Transputers have inter-processor communication interfaces included on-chip.

1.8 Direction and scope of this research

This dissertation describes the theoretical and practical research work involved in the analysis, design, implementation and validation of the proposed new electromagnetic vehicle suspension control strategy.

In order to validate the proposed control strategy, a small experimental vehicle chassis (capable of carrying one person) was constructed and equipped with an implementation of the proposed suspension control system. Since the lateral motions of the vehicle do not suffer from problematic cross-coupling, electromagnets to provide lateral force actuation were not employed. This results in only four electromagnets rather than eight being required, which significantly reduced the cost and complexity of the experimental vehicle. The electromagnets, track and linear induction motor from an earlier research project were provided for use with the new experimental vehicle. A single electromagnet experimental rig was also constructed to facilitate algorithm testing on an independent suspension configuration.

This account of the research work is partitioned into seven chapters as listed in Table 1.3. In each chapter the theoretical basis is described and then results from the experimental systems are discussed and conclusions are drawn.

Table 1.3 Summary of the research work

1	General literature review and proposed research strategy.
2	Analysis of the electromagnet force characteristic.
3	Synthesis of the electromagnet force control algorithm.
4	Analysis of an independent mode suspension and synthesis of the control algorithm.
5	Analysis of the vehicle motions and synthesis of the vehicle control system.
6	Selection/development of the hardware and software for the control system.
7	Overall conclusions and identification of areas for further research.

In Chapter 2 the steady-state and dynamic behaviour of the electromagnets used on the experimental research vehicle is analysed. Equations are developed which model the steady-state lift and lateral forces in terms of core dimensions, air gap, coil current and lateral displacement. The models include the effects of air gap flux fringing, leakage flux between the electromagnet poles pieces, and the variability of core permeability due to saturation effects. Dynamic model equations are developed for the flux lag time constant due to the electromagnet coil circuit and the eddy current circuits within the electromagnet and rail cores. The model for the flux lag time constant is a function of the core dimensions, air gap, number of coil turns, coil resistance, core construction and core material resistivity.

Chapter 3 describes the analysis of the performance of various feedback control strategies in terms of their capability to reduce the instability and nonlinearity of the electromagnet force characteristic. The strategies considered include feedback of force, flux, rate of change of flux, acceleration, air gap and current. A novel feedback control algorithm is then proposed using only air gap and current feedback, and embodying the detailed electromagnet model developed in Chapter 2.

In Chapter 4 the requirements for an independent suspension are analysed. A suspension control scheme is then proposed which consists of two separate functions. Firstly, a track coupling algorithm uses the measured track position to determine a required suspension position. Suspension positioning with disturbance force rejection is then performed by a state feedback mode position controller which incorporates acceleration, velocity, position error and position error integral feedback. All feedback signals for the proposed scheme are derived from measured values of acceleration and air gap. The validity of the proposed strategy is then tested using simulations and an experimental single electromagnet suspension rig. Since the experimental vehicle track has no significant gradients, a second-order, low pass filter is used for the track to suspension coupling algorithm to obtain experimental results.

In Chapter 5 the suspension requirements for the complete multivariable vehicle suspension are analysed. The transformations required to decouple the electromagnet motions are identified so that independent vehicle mode control loops can be realised. Extensive experimental suspension tests covering stability, mode decoupling, ride comfort over simulated rail steps, disturbance force rejection and linear motor force coupling are then presented and evaluated.

Chapter 6 describes the implementation of the experimental vehicle control system. First, the development of the electronic hardware for the control system and the selection criteria for the feedback sensors are described. Hardware development includes closed-loop electromagnet current controllers, a transputer module motherboard, transputer based analogue to digital and digital to analogue converter cards, and fibre optic interface cards for the transputer communication links. The structure of the concurrent software which implements the vehicle suspension control algorithms is described next. Topics include selection of sampling rate, discrete digital implementation of the continuous time design, required numerical accuracy of the digital processors and finally it proposes a scalable multi-processor configuration strategy which can efficiently utilise one processor per electromagnet. Practical implementation features such as real-time data monitoring and logging, control of vehicle suspension startup and shutdown, and system fault detection are also included in the experimental system design.

The last chapter draws overall conclusions about the success and limitations of the results of this research and suggests some areas for further work.