Electrical Mechanisms: A merger of mechanisms and electrical machines

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Abstract

We present a synthesis of the areas of electrical machines and mechanisms, and present a new set of devices called electrical mechanisms (emecs). The key generalization is to make the electrical prime mover part of the mechanism itself, with geometry not restricted to being either cylindrical as in rotary motors, or linear as in linear motors. The geometry of the electromechanical interactions, is dictated by the geometry of the mechanism itself, and interactions are potentially present at every joint.

Our ideas offer better controllability of the mechanisms, due to the cancellation of singularities across different input-output pairs. When one input output pair has a zero in the transfer function, another has a non-zero, offering high accuracy multi-variate control.

The ideas can be used in either an active excited coils or permanent magnets. These passive versions have become practical with the advent of high power rare earth magnets. Power levels are comparable to medium power pneumatics. These ideas are illustrated with a number of applications.

Keywords: Mechanism Theory, Machines, Electromechanical Systems.

1. Introduction

Mechanisms achieve desired positional, trajectory or function generation based on the interaction between rigid members (links) and their connections – upper/lower pairs [Ghosh-Malik 3, Uliker-Shipley -2, Ghoshal 1) When powered using electrical means, such mechanisms have been traditionally driven by electric motors, either cylindrical or linear in geometry. Based on standard Lagrangian/Hamiltonian techniques, and the mechanism constraints expressed by, say DH 1 parameters, equations (generally nonlinear) of motion of the mechanism can be derived. These equations, relating a set of input/actuated links to a set of output positions, in general exhibit Jacobians which vary from being well-conditioned to singular, complicating control (Ghoshal 1). Energy minima/maxima also appear, referring to stable/unstable states of the mechanism.

The primary determinant of this complex dynamics is the nonlinear input-output coupling provided by the mechanism. Other than in simple mechanisms, this coupling is critically dependent of the state of the mechanism. At singular points, the mechanism can lose (serial and parallel mechanisms) or gain degrees of freedom (parallel manipulators).

Note that the dynamics of the system are determined by the combination of the kinematics determined by the mechanism design, as well as the potential energy in each mechanism configuration in terms of generalized coordinates. This coupling of kinematics to dynamics complicates mechanism control.

Dynamics can be partially decoupled from kinematics through the choice of an appropriate potential energy function. Changing the potential energy function enables the dynamics to be changed, keeping the kinematics invariant. While the gravitational potential energy cannot be conveniently controlled, springs, pneumatics, hydraulics, etc can be used as controllable reservoirs of P.E, but typically cannot operate at high speeds due to inbuilt inertia, require expensive sealing, etc.

The most convenient form of P.E. is electromagnetic, which is high speed, predictable, repeatable, and non-contact eliminating wear and tear issues. Losses in electromagnetic systems can be controlled through well known techniques like laminations, proper materials, etc. Till recently, however, electromagnetic P.E. was relatively small compared to alternatives. The recent development of high-power rare-earth (Neodymium and/or Samarium-Cobalt) magnets, offering inexpensive fields with strengths approaching 1 Telsa, and power comparable to medium power pneumatics (See Table 1) has opened new vistas for customizing the dynamics of mechanisms, and this is the topic of this paper.

This incorporation of customizable electromagnetic forces in the mechanism, leads to a synthesis of electrical machinery and mechanisms, and yields a new class of devices called electrical mechanisms (emecs). The electromagnetic fields in emecs are not resticted to either cylindrically symmetric or linear geometries, but track the mechanisms kinematic paths.

Our techniques to configure dynamics can be used in conjunction with other well known methods including gravitational assist, springs, electromagnetic forces due to magnets, hysteresis/induction loads, etc. Our methods can be applied to mechanisms incorporating lever arms, gears etc, with well known methods for handling them (Erdman and Sandor [13], Sandler, Ben-Zion [14], Uicker, Pennock & Shigley 2, Ghosh & Mallick 3, Ghosal 1, Myszka 4). Below, we first discuss the capabilities of modern rare earth magnets.

2. Capabilities of Modern Rare Earth Magnets

We begin by discussing the energy levels available, follow up with a discussion of forces and damping constants available. In general, modern high power magnets are approaching energy levels offered by low end pneumatic systems, while being more flexible and cost-effective.

Energy Levels

The energy stored per unit volume in a field of B Teslas, in a unit permeability substance is given by:

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$$E_m = ½\ 1/\mu_0\ B^2 = ½ * 1/(4*\pi * 10^{-7}) * 0.5^2 = 100\ KJ/m^3 \text{ at } 0.5T$$

For fields between 0.5 to 1T, the stored energy varies from 100 KJ/m^3 to 400 KJ/m^3.Such fields are easily generated using commonly available (N35 or N45) Neodymium-Iron-Boron magnets (N45 is about 15-20% more energy dense than the N35). Variants of N35/N45 are available, with maximum operating temperatures of 80 to 150 degrees C. These permanent magnets are superior to electromagnets – with higher energy densities and lower losses. By comparison, the energy levels offered by low cost ceramic magnets are an order of magnitude lower.

	Strength	Energy Density (KJ/m3)
Magnetic Field (Tesla)	0.50	99.47
Electric Field (V/m)	3.00E+06	0.04
Gravity at height of 1 m	1.00	78.40
Kinetic Energy @ 10 m/s	10.00	400.00
Pneumatics (Isothermal) Mpa	0.5	804.72
Pneumatics (Adiabatic γ = 1.4) Mpa	0.50	460.77

Table 1: Energy Levels offered by various forces

Table 1~~Table 1~~ compares magnetic energy levels with those produced by different kinds of forces, under comparable conditions.

In Table 1~~Table 1~~ the maximum obtainable electric field energy per unit volume without breakdown in air is given by

$$E = ½*e*E_{BV}^2$$

Where E_{BV} is the breakdown voltage of air, about 3 Million volts per meter.

The gravitational potential energy is given per unit volume and unit height as a

$$E = \rho\ g$$

where ρ is the material density (about 8000 Kg/m_3 for magnetic materials).

For pneumatics, the stored energy per unit volume, at pressure P_1 working isothermally against standard atmosphere P_2 is:

$$E_p = P_1*\ln(P_1/P_2) = 1MPa*\ln(1MPa/0.1\ MPa)$$

We note that high speed expansions are polytropic (closer to adiabatic) instead of isothermal, resulting in lowered energy densities. For polytropic expansion (PV^{γ}=C), we have

$$E_p = P_1/(\gamma-1)*(1-(P_2/P_1)^{(\gamma-1)/\gamma})$$

Barring high pressure pneumatics, the magnetic field energy is the highest per unit volume. Since magnetics does not require mechanisms to handle high pressure air, there are many interesting applications in mechanism design.

Magnetic Springs: Magnetic Attraction/Repulsion

Against this background of rare earth magnets having high energy densities, we can examine the forces obtainable using them. Since the magnetic forces depend strongly on the relative position of interacting magnets, very high spring constants, which can be *customized easily* by changing the dimensions, geometry, and/or relative position of one or more magnets can be obtained.

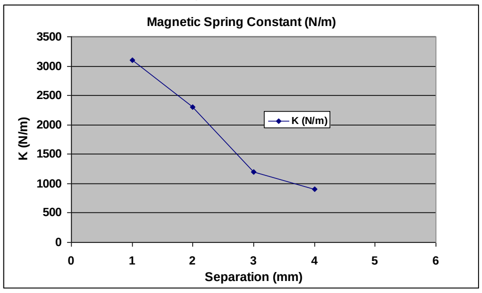

Figure 1: Magnetic Spring Constant 1cmx1cmx1cm magnets arranged to repel each other

Figure 1~~Figure 1~~ shows the spring constant obtained from the repulsive force between two small N35 Neodymium magnets 1cm x 1cm x 1cm in size. FEM analysis was used to obtain this force. Figure 1~~Figure 1~~ shows that dramatic changes in spring constant from 3100 N/m to 900 N/m can be obtained with very small changes (5-10 mm) in relative positioning, facilitating nonlinear interactions when used in mechanisms. The higher magnetic strength N45 has about 15-20% higher energy/force levels.

Magnetic Dampers: Inductive and Hysteresis Based

Damping due to magnetic forces can be based on either hysteresis or induction effects. We shall concentrate on induction effects in this discussion. The induction force on a conductor moving with velocity v, at right angles to a field of B Teslas, is given by:

$$F = \alpha\ \sigma\ v\ V\ B^2$$

Where σ is the conductivity of the conductor, α is a geometry factor, and V is the volume (product of the width, length and thickness) of the region of interaction between the conductor and the field. This equation holds for velocities small enough for the induced field to be neglected. Since the energy density is given by

$$\underline{E_m = ½\ \mu_0\ B^2}$$

The force equation may be rewritten as

$$F = 2\ \alpha\ \underline{\mu_0}\ \sigma\ v\ V\ \underline{E_m}$$

Note that in addition to the energy density $\underline{E_m}$, the conductivity σ, and the geometry factor α also determine the force. The damping coefficient (Force/Velocity) for Copper turns out to be

$$F/v = 145\ \alpha\ Em\ V \qquad (1.1)$$

This yields damping densities of 15 N/(m/s) per cubic centimeter, at 0.5 Tesla. Note that the presence of both the geometry and the volume factors shows that the damping coefficient can be easily changed as a function of position, by changing the physical dimensions, geometry, and relative orientation of the conductors and magnets involved.

The power dissipated due to inductive effects (for copper) is clearly

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$$P_M = Fv = \alpha\sigma B^2 V^2$$

$$\frac{P_M}{P_{K.E.}} = \frac{\alpha\sigma B^2 V^2}{\frac{1}{2}\rho V^2} = \frac{\alpha\sigma B^2}{\frac{1}{2}\rho} = \tag{1.2}$$

$$\frac{5.9x10^7 S/m\, 0.5^2 T^2}{\frac{1}{2} 8000 Kg/m^3}\alpha = 3687.5\alpha \gg 1$$

The ratio of the power dissipated to the kinetic energy is independent of velocity, and approximately 4000 for copper. This implies that the braking force is very strong relative to the stored kinetic energy – magnetic braking is very fast, even after geometry effects incorporated in α, and non-magnetic portions contributing solely to mass and K.E, are accounted for. Clearly the presence of magnetic damping can significantly impact mechanism dynamics.

3. Electrical Mechanisms (EMECs)

From a viewpoint of mechanisms, an electrical motor or generator (Figure 2~~Figure 2~~) is a mechanism composed of a single powered revolute pair (for rotating machinery) or a prismatic pair (for linear motors). Energy is pumped in/extracted at the single joint, from the stator-rotor system for rotating machines, and the track-follower system for linear machines.

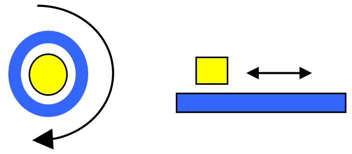

Figure 2 Rotary and Linear Motors

When used to power a mechanism (e.g. a robot manipulator), these motors are used to actuate one or more pairs, and jointly controlled, as shown in Figure 3~~Figure 3~~, where mechanism M is driven by two rotary (R1, R2) and one linear motor (L). The driven mechanism M and the motors driving it are distinct, each with their own dynamics. Optimal control couples the separate dynamics of R1, R2, L, and M to achieve desired motion control, and has to deal with the varying condition numbers and/or singularities of the relevant kinematic/dynamic Jacobians.

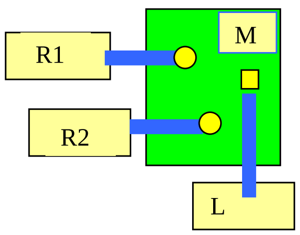

Figure 3 Mechanism driven by two rotary and one linear motor

Our key contribution is to *merge* the motors (or generators) into the mechanism, and treat this as an *active* mechanism directly. In doing so, a number of issues are encountered:

- The merger, if non-trivial, has to change the *identity* of the motors. By change of identity we mean that the different parts of the motor *can no longer be identified as a separate complete motor, attached at a point in the mechanism*. Otherwise, we get the well-understood multiply actuated mechanism, where different actuators are excited in a coordinated fashion 6, 7. Rather, the different portions of the motor are spread throughout the mechanism. Different ways of doing this lead to different classes of electrical mechanisms.
- The control of the original multi-motor-mechanism system becomes transformed into the control of a single mechanism, with possibly multiple points of actuation.
- The design has to be efficient – the revolute (prismatic) joint in rotary (linear) motors can very easily maintain an accurate air gap critical for high power/speed operation.
- Any losses due to hysteresis/eddy-currents have to be minimized.
- Effects of temperature and repeated cycling on permanent magnet interactions have to be minimized – modern rare earth magnets can operate upto 100 ºC and beyond.
- The mechanism becomes a special purpose machine, but can be cost-effectively manufactured using modern CAD/CAM.

4. EMECs: Enhanced Pairs

Broadly speaking, a taxonomy of electrical mechanisms can be made on the basis of the type of and location of the electromagnetic interactions in the mechanism.

Interaction Type:

i. Lossless Interaction: Here the electromagnetics is used to store and return energy in a lossless fashion, offering an electromagnetic spring. Mechanical bistables, astables and monostables can be designed using these conservative interactions. Figure 1~~Figure 1~~ shows that spring constants of 1000’s N/m are obtainable with small magnets.
ii. Dissipative EM interactions: Here the electromagnetics is used to “brake” the mechanism, and essentially offer customizable damping. From Section 2, damping constants of around 15 N/(m/s) can be obtained with small magnets.
iii. Hybrid interactions: In general both dissipative and conservative interactions can exist.

Interaction Geometry:

By definition, a mechanism is composed of rigid links connected together by joints. Enhancement of either links or joints (pairs) by electromagnetically interacting entities results in an electrical mechanism.

i. Type A: Interaction Localized at Joints: Mechanisms can have electromagnetic interactions at the

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joints (constant air gap) only (we shall primarily discuss these - Figure 4~~Figure 4~~).

In general, a pair which is actuated need not have magnets co-located at the joint itself, but these can be attached to various links associated with the joint. All that is required is that the electromagnetic force is a function of one joint variable only, in which case the enhancement can be associated with the respective pair.

ii. Type B: Distributed Interaction: EM interactions can be distributed throughout the mechanism, with links interacting (Figure 6~~Figure 6~~). Analysis/design of the former structures requires extensions of classical methods applicable to rotating machinery. Distributed electromagnetic interactions require full blown electrodynamic equations to be solved, under mechanism constraints.

Type A: Interactions at Joints: Figure 4~~Figure 4~~ shows a revolute joint with electromagnetic interactions, with magnets (permanent and/or electromagnets) on the pins and the housing, coupled with conductors and/or magnetic material. The magnets provide customizable losses storage/release of energy, while the conductors/magnetic materials provides eddy current/hysteresis damping. *The key difference between installing a motor at this pin and the shown structure is that the spacing of the magnets and the strength need not be equal but designed to suit a desired mechanism dynamic criterion, by modulating the potential energy and damping constants of the system*. For example, Figure 4~~Figure 4~~ (a) shows a configuration in which two north/two south poles are adjacent in the "rotor" of this revolute pair – in a motor south and north are interleaved with each other. In Figure 4~~Figure 4~~ (b), north and south poles are near each other, resulting in a stable state of the joint, while the opposite is true of the position in Figure 3 (c). The resulting potential energy surface has minima in configuration (b), and maxima in (c). The P.E and damping constant for the complete mechanism is clearly the sum respectively of the P.E. and damping constants of the configuration of all joints, and can be designed to suit a desired dynamics.

$$\text{P.E.}(q_1,q_2,q_3,\ldots) = \Sigma\, \text{P.E}_i\,(q_i) = \Sigma \int ½\, \mu\, B_i^2\, dV \quad (1)$$
$$K(q_1,q_2,q_3,\ldots) = \Sigma\, K_i\,(q_i) = \Sigma \int ½\, \alpha_i\, \sigma_i\, B_i^2\, dV$$

We have used the fact that the potential energy per unit volume is given by ½ μ B^2, and the damping constant due to eddy currents per unit volume of material per unit velocity being given by $\alpha\ \sigma\ B^2$, where σ the conductivity, and α a geometry constant (Section 2). It is clear that the same ideas of placing lossless magnetic storage and/or dissipative elements can be used for *all the pairs* used in mechanisms. For example, Figure 5~~Figure 5~~ shows a prismatic pair enhanced with both magnets and dissipative members (not shown for clarity) on both the sliding member (link1) and the guide (link 2), offering customizable stable states and damped dynamics.

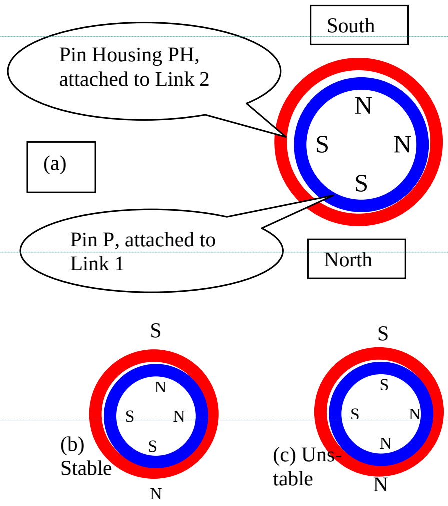

Figure 4: Electromagnetic interactions confined to the joints

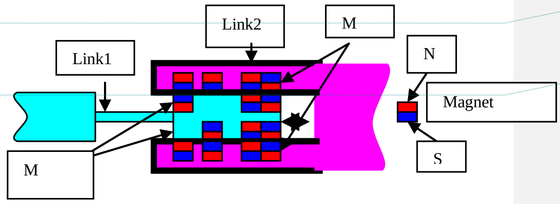

Figure 5: Prismatic Pair enhanced with magnets and/or dissipative members

In general local minima (stable/unstable states) manifest themselves, creating mechanical monostables, bistables, and astables if energy is injected into the mechanism. Note that the potential wells of different joints are designed independent of each other, as long as the electromagnetic fields are restricted to the joints. Thus extensive customization of possibly multi-modal energy functions is offered by these mechanisms. A detailed example for the flywheel of an IC engine, is shown in Section 7

Kernel, what should you build beyond ready-made motors. Anything more than rotary / linear?

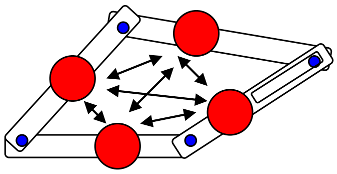

Figure 6 Distributed Electromagnetic Interactions in a 4-bar linkage

Type B: Distributed Interactions: Here the electromagnetic fields extend beyond the immediate vicinity of pairs, and long range interactions exist (see the magnets in the 4-bar linkage (with one prismatic pair) in Figure 6~~Figure 6~~). Here, the energy function cannot be accurately separated into parts depending only on a single pair configuration, and is globally dependent on the entire system configuration. The Lagrangian has to incorporate this global system function.

5. EMECs: Composition of Pairs

Design of such mechanisms, composed from pairs can be conveniently described by a two-step process.

- The kinematics specifications (motion, path, function generation, etc) are used to determine the type of the mechanism – 4-bar linkage, crank-rocker, etc.
- The dynamical specification as reflected in the Lagrangian and its extrema are used to design the electromagnetic interactions. The specification contains the specification of the stable states, as well as the desired damping constants (and other linear/nonlinear dynamical parameters) between them.
- Actuation can be placed at one or more of the joints, can be used for powering the mechanism. The multivariate control strategies used have to account for the non-cylindrical and nonlinear nature of the actuators which are in general neither completely rotary nor linear motors.

  Note that the influence of the kinematics on the dynamics, as reflected in ill-conditioned/singular Jacobians [Ghoshal 1] and equivalent mass matrices, can be countered to an extent by a suitably chosen and deep potential well or peak at that configuration. (see the detailed example below). Since electromagnetic interactions allow easy and repeatable customizability of potentials, the dynamical design becomes substantially decoupled *from the kinematics beyond this point.* Simply put, where the mechanism is hard to move, put a few magnets to internally push it on its way, and vice versa.

We illustrate these ideas by considering a 4R mechanism shown in Figure 7~~Figure 7~~. Each of the revolute pairs can be either free, without any magnetic interaction attached (white), or can have either passive magnetic interactions (using permanent magnets - blue), or can have actively powered coils (red). Different choices for the revolute joints result in different kinds of mechanisms. Since there are 3^4=81 different configuration, we shall only discuss a few important cases. We will assume that the base fixed link is AD in all cases.

- In Figure 7 (a), only joint A has permanent magnets on the rotor and stator , following the structure in Figure 4. This is a *stepper mechanism* (as opposed to a stepper motor). These stepper mechanisms in general have positions on a non-uniform grid, with different holding torque/forces. In (a), when BC and CD are collinear, the mechanism is in a singular configuration, and the finite holding force/torque at A cannot prevent C from moving.
- This can be fixed by the structure in Figure 7 (b), where both A and D are enhanced with magnets. It is clear that no configuration exists wherein the Jacobians from both A and D to C are singular simultaneously. Both A and B can be designed to compensate for each others singularities, and each may optimally operate for only a portion of the mechanism's state. Since the manipulator is being held redundantly, the forces can be chosen to satisfy a given metric, e.g. the L_2 norm, the minmax L_∞ norm, etc (Ghosal **Error! Reference source not found.**, Nakamura 5). We have the holding force equation

  F(q) = K1(q) FA(q) + K2(q) FD(q)

Where K1 and K2 are the force transmission matrices from A and D to C, in configuration q. For construction, the L_∞ norm is suitable, since then the maximum field strengths at each enhanced joint are limited. If θ is the angle BAD, then static analysis yields:

Note that in configuration (…) the floating link is actuated, which may not be desirable.

Stable states are on the kinematic paths, and the joints can be designed to optimally have a certain holding force. No dwell state.

For a 4-bar linkage, no singularities exist if it is activated all 4 points and in general at any 3. It is controllable in any configuration.
With passive permanent magnets, it can be controlled even with a single actuator, as long as the direction of motion is unidirectional?
With flippable magnets, bi-directional control can be achieved.

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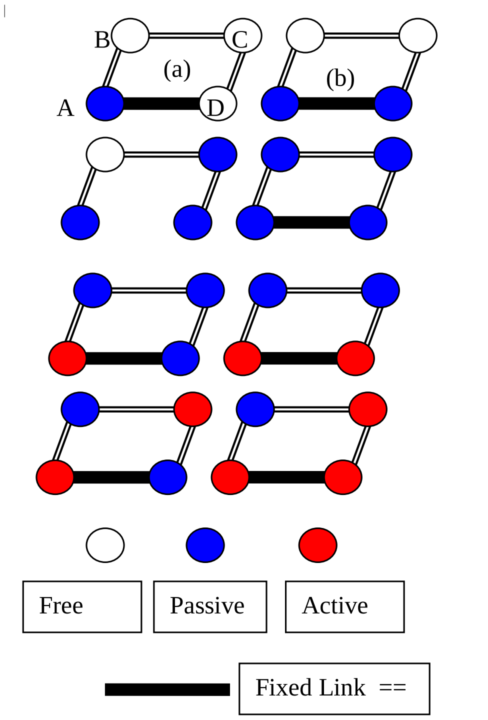

Figure 7: 4R mechanism enhanced with magnets

Based on this, after the mechanism type has been selected, the P.E. and K terms in equations (1) can be written as a function of configuration as

$$\Sigma\, P.E._i\,(q_i) = \Sigma \int \tfrac{1}{2}\, \mu\, B_i^2\,(q_i)dV = P.E.(q_1,q_2,q_3,\ldots)$$

$$\Sigma\, K_i\,(q_i) = \Sigma \int \tfrac{1}{2}\, \alpha_i\, \sigma_i\, B_i^2\,(q_i)dV = K(q_1,q_2,q_3,\ldots)$$

where the total P.E. and K is specified and hence moved to the R.H.S.

For type A mechanisms, design of such devices begins with a decomposition of the P.E. and K functions into portions implementable on separate pairs, and is clearly an *eigenfunction expansion (in terms of sines/cosines, Chebychev polynomials, etc)*, allowing approximations varying from optimizing the L_2 (mean square error) to the L_∞ (minmax norm). If a Fourier expansion is used, we have:

$$\int \tfrac{1}{2}\, \mu\, B_i^2\,(q_i)V = A \cos(2\, p\, N\, q_i + \phi_i)$$

where there are N pole pairs in one pair member and a single pair on the other (Figure 4~~Figure 4~~). The spatial phase factor ϕ_i is determined by the orientation of these pole pairs w.r.t a base axis. The number and strength of poles on each joint (pair) can be optimized – see the detailed example in Section 6.

Each pair is designed in a decoupled fashion to implement the basis function assigned to it. Standard electromagnetic design techniques to shape the magnets and/or induction/hysteresis members can be used to implement sine/cosine basis functions, Chebychev polynomials, etc. Varying strength magnets can be used to implement the constants in the eigenfunction expansion.

Type A Mechanisms: A sinusoidal basis function can be designed using the structure shown in Figure 8~~Figure 8~~, whose energy function is shown in Figure 9~~Figure 9~~. A set of alternating pole pairs on one link interacts with one or more (altenating) poles on another link, resulting in the energy function having maxima when like poles face each other, and minima when unlike poles face each other. FEM analysis allows the determination of the optimal shape of the pole pieces for spectral purity of the implemented energy function.

The energy function using FEM analysis for two rectangular N35 magnets, each 10mm across, with a thickness of 3mm, has been carried out and the magnetic energy determined as a function of position. The energy well is shown in Figure 10~~Figure 10~~ (a), and its spatial spectrum in Figure 10~~Figure 10~~ (b) (after removing the constant component, which does not impact dynamics). Clearly the magnetic field furnishes an energy well whose spatial spectrum has a peak at one every 30 units, which is a function of the magnetic element geometry. Harmonics are 6 dB down at least, furnishing an approximate sinusoidal energy function. Shaped magnets, if they can be economically manufactured in large quantities can yield sharper spectra. The fields obtained in this manner can be used to expand any desired energy function to implement a desired dynamics.

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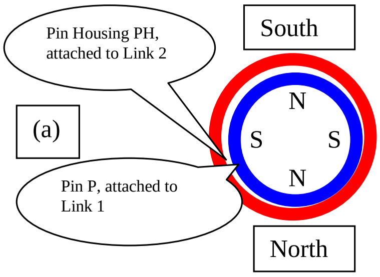

Figure 8: Revolute Pair Implementing Basis Function

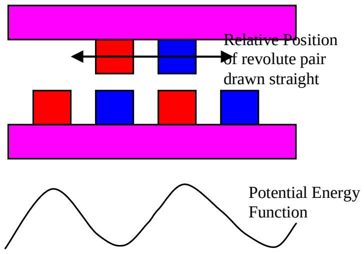

Figure 9: Energy Function of Revolute Pair drawn straight with rectangular poles.

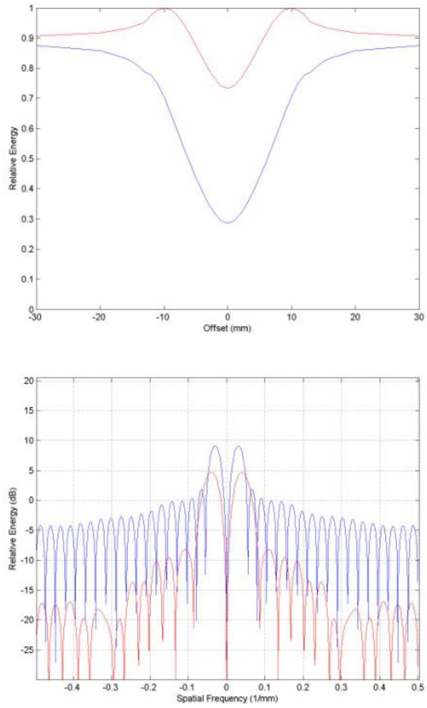

Figure 10: (a) Energy Well and (b) Fourier Spectrum.

For type B mechanisms, the P.E. cannot be decoupled and nonlinear optimization techniques have to be used to directly implement the P.E. and K functions taking the electrodynamics of the mechanism as a whole. Details are the topic of other papers.

6. Examples

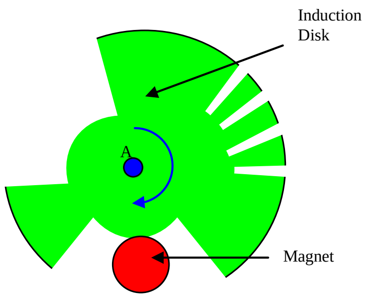

Figure 11: A non-uniform timing electromagnetic revolving cam

In this section, we present a few examples of mechanisms which illustrate the power of our ideas. Figure 11~~Figure 11~~ shows an electromagnetic cam where a dissipative induction brake (assumed to be copper) has been cutout and shaped to offer a time varying load to the prime mover, which typically would be geared down. From Equation (1.2), the braking power is substantially greater than the kinetic energy, leading to potentially millisecond response times. At 0.4 Tesla, a 1 cm x 1 cm magnet induces a 1 gm force in a 1mm induction member (Equation (1.1)), which is comparable with forces and torques produced by minimotors. Hence time varying control of such devices can be achieved by purely passive methods, without microprocessor based control. Applications encompass a wide space – low cost toys through high reliability spacecraft mechanisms.

Similar control of dynamics can be achieved in a lossless fashion, and this will be discussed in the IC engine example below.

7. Application to an IC Engine

One major application of the slider crank mechanism is in IC engines. Our ideas can be used to smooth the torque ripple due to the engine periodic stoke based operation.

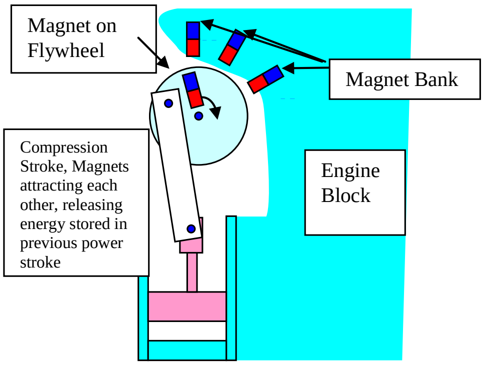

Figure 12: Engine (*simplified sketch*) with Flywheel and Block enhanced with Magnets, permitting storage of engine power magnetically.

One such mechanism converts the flywheel to a non-uniformly magnetically enhanced revolute pair. Figure 12~~Figure 12~~ shows a 2-stroke IC engine sketch with a flywheel (and engine block) which is enhanced with magnets, yielding an enhanced revolute pair. The strength of the magnetic interactions in the revolute pair changes with angular position, in a manner to absorb energy during the power stroke and return it ideally losslessly during the compression stroke. Ignoring the magnets for the time being, the pulsating torque and hence speed produced by an IC engine requires a flywheel to be smoothed, and this can be dimensioned using energy balance 3.

$$\frac{1}{2} J \left(\omega_{\max}^2 - \omega_{\min}^2 \right) = \Delta K.E$$
$$\Rightarrow J = \frac{2 \Delta K.E}{\omega_{\max}^2 - \omega_{\min}^2} = \frac{\Delta K.E}{\omega_{avg}\, \delta\omega} = \frac{\Delta K.E}{\omega_{avg}^2 k_s} \quad (1.3)$$

where k_s is the maximum percent ripple in speed.

The enhanced flywheel system in Figure 12~~Figure 12~~ uses high-power magnetics allows an alternative means of torque smoothing. The key idea (2-stroke engines) is to store the power stroke energy in a magnetic field, by pushing unlike poles away, and releasing this energy in the compression stroke by bringing them together (or vice versa). Figure 12~~Figure 12~~ shows a single magnet on the flywheel, interacting with magnets on the engine block. The resultant unbalanced torque and shaking forces can be cancelled by two oppositely directed and offset magnets – details of the actual mechanical structure used are omitted for brevity. 4-stroke engines can also be handled with auxiliary mechanisms.

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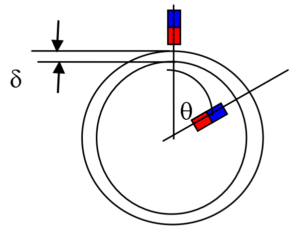

Figure 13: Torque produced by magnets

Following Figure 13~~Figure 13~~, an approximate expression for the torque produced between two elementary magnet poles at an angle θ, with a minimal air gap δ, is given by

$$\tau = \frac{\tau_{max} \sin \theta / 2}{2R \sin \theta / 2 + \delta^{2}}$$

For macroscopic magnets, an integral over the pole distribution has to be carried out, and is done using FEM techniques and is shown (Normalized Torque) in Figure 14~~Figure 14~~ .

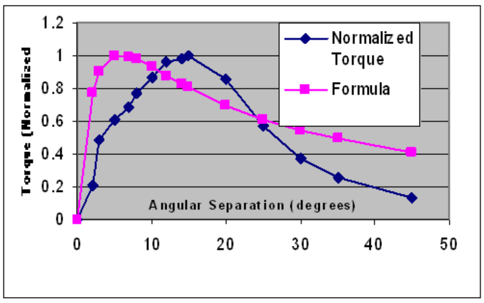

Figure 14: Torque for pole pair vs angular Separation.

The net torque produced by the distribution of magnets over the entire circumference of the flywheel is calculated at each angular position of the crank, and algebraically added to the engine output. The resulting torque (which is non-uniform to match the engine pulsations) profile is analyzed for residual ripple. The magnet distribution is optimized using a nonlinear optimization procedure to minimize this residual ripple.

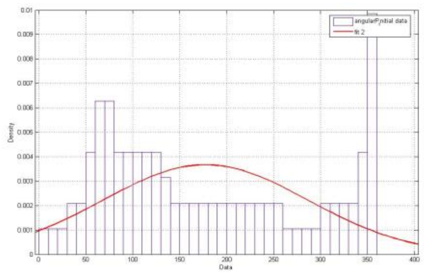

Figure 15 Magnetic Structure of engine block magnets used in conjunction with Enhanced Flywheel

Figure 15~~Figure 14~~ shows the magnetic structure used in the engine block – the initial portion corresponds to the power stroke, where the engine does work against the attracting force of magnets. Each magnets is in an attracting position, pulling the rotor towards itself. At the very beginning of the power stroke, the large magnets peaking around 60 degrees pull the flywheel forward, offering additional power at the beginning of the power stroke. During full combustion, the flywheel is pulled away from these magnets, leading to energy storage in the magnetic field. Residual energy from this power stoke, is absorbed by the magnetic system, till about 300 degrees, at which time the large magnet towards the end starts compressing the gas for the next power stroke, using the energy stored previously.

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Parameters	Values
Piston Diameter	90mm
Crank Radius	60mm
Connecting Rod	240mm
Speed	1800 RPM
Fly Wheel Diameter	300mm

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Table 2 Engine Parameters

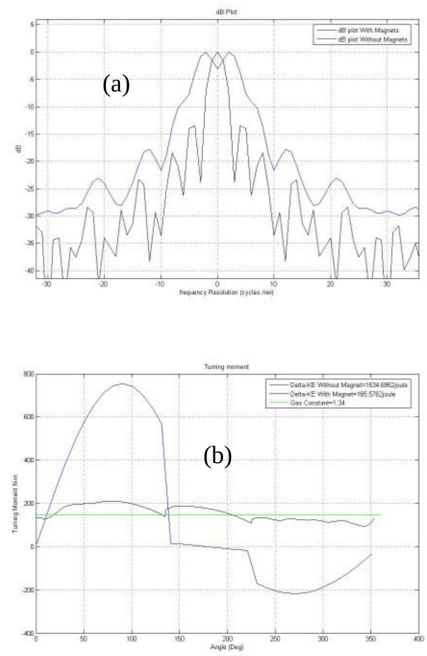

Figure 16: Harmonics (a) and Residual Ripple (b)

This procedure was adopted for the 2-stroke engine parameters shown in Table 2~~Table 2~~. The results are shown in

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Figure 16~~Figure 15~~. Energy has been transferred to the fundamental constant component, raising it by 2.5 dB. The first harmonic (1 cycle/rev) is the same, while the second harmonic has been reduced by 5 dB – the other harmonics are much lower. All the magnets (about 100, each about 3cm x 1cm) can fit within the flywheel space, and provide both inertia energy storage and magnetic energy storage. Changing the magnet profile allows the residual harmonics to be optimized as required (details omitted for brevity). The change in K.E., and residual ripple is down from 1530 J to less than 200 J, a factor of 10. The results remain qualitatively the same even with varying engine indicator diagrams with γ ranging from 1.2 to 1.4. The results are even better for multi-cylinder engines.

We stress that as opposed to ISAD's (integrated starter alternator dampers), we pre-configure the (non-uniform) magnetics to passively reduce if not eliminate engine harmonics. It is the non-uniformity of the magnetic interactions which differentiates this technique from an ISAD, where the non-uniform dynamics is obtained due to active control. The residuals, can of course be corrected with active control techniques, e.g. ISAD's.

Clearly, we can equally well do the reverse of torque smoothing – by an appropriately arranged magnetics, we can convert a constant torque to one with harmonics – e.g. for a vibration testing jig. Indeed the same configuration of magnets, when driven by a constant torque will generate harmonics at the reciprocating end, which can be customized, by varying the same magnet profile. Additional customization can be had by putting magnets at the reciprocating end itself. For example, if two like (unlike) poles are brought together at the end of the stroke, the mechanism will be braked hard (brought together fast), and then released at high speed (braked hard), leading to a jerk type (suddenly stopped) excitation. All this is done passively, but enhancing the pairs of the mechanism with customizable magnetic energy

8. Conclusions

We have present a synthesis of the domains of mechanism and electrical machinery, and discussed a new class of devices called emecs. The key idea is to use in-built non-uniform electromagnetic interactions to achieve desired dynamic behavior (including stable states), which are appropriately matched to the kinematic behaviour or excitation of the mechanism. We have shown that emecs offer advantages in applications like torque smoothing of IC engines, vibration testing rigs, timing cams which can be customized, etc.

9. References

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If there are K desired rest positions for the apparatus, then the magnets in the pairs/joints will have O(K) poles.

- In an exemplary design for a mechanism with one degree of freedom, with only revolute joints (pins and housings), only one pin is magnetized with K North-south pole pairs, the housing has a single N-S pair, and the rest are non-magnetic. A simple algorithm to determine the pole locations is to place a N-S pair on the pin, aligned with the S-N field on the housing in each desired rest-state. In general, the resulting N-S pairs may be close together, in which case, multiple pins can be magnetized, with each pin having rest-positions at a subset of the rest-states of the whole mechanism. *The selection of these subsets can be made in a manner as to optimize criteria such as maximizing holding force, positioning accuracy, etc. Exemplarily, to maximize positioning accuracy of any point on a link of the mechanism, the pin most sensitive to changes in the aforesaid point's position can exemplarily have a rest-state corresponding to each desired location of the aforesaid point*. Multiple pins/housings may be magnetized at the same desired locations, possibly yielding higher holding forces, for both single-degree of freedom mechanisms, and multiple-degree of freedom mechanism. The number of N-S pairs in each pin/housing may in general differ.
- In general, dynamic motion between two states can be controlled by any of the variants using possibly induction/hysteresis effects, multiple autonomously magnetic interacting members, induction/hysteresis members of different geometry, etc. as per Section **Error! Reference source not found.**. Exemplarily, these forces can be used to slow down "ratcheting" between states – e.g. the ejector/latch **Error! Bookmark not defined.**.

Connecting links and joints/pairs enhanced in the aforesaid manner as per the invention, enables creation of mechanisms of arbitrary complexity ranging from 4-bar linkages and its variants (including quick-return mechanisms), Geneva Mechanisms, the Watt Chain, the Stephenson Chain**Error! Reference source not found.**, Chebychev's walking mechanism**Error! Reference source not found.** (exemplarily, here the rest states can be designed to fold the legs in a crouching position) etc. *An advantage of this invention is that the motion between the states is noiseless, unlike ratcheting alternatives well known in the state of art.*

Power Control, Power Transmission Control, and Load Control can be generalized to general mechanisms– 4-bar, Geneva, etc. **Error! Reference source not found.**, **Error! Reference source not found.**, possibly including angular displacements, multiple degrees of freedom e.g. 3-axis translation + 3-axis rotation, etc. Our definition of a general mechanism includes apparatus whose parts may be *partly or completely unconstrained* (e.g. the carom board **Error! Bookmark not defined.**) with respect to each other.

1. Power Control:
   Here we consider generalizations of electric motors, with possibly changing fields produced by powered windings and/or permanent magnets on portions of the mechanism, interacting with possibly changing fields in other portions, possibly produced by powered windings and/or permanent magnets. The methods of Section **Error! Reference source not found.** can be used to modulate both the flux, and the forces/torques possibly due to induction/hysteresis effects. The key generalization over the existing state-of-art in electric motors, and solenoid actuators, is that general non-circular/non-cylindrical geometries, possibly having multiple regions of electromagnetic interactions producing force/torque, are considered.
2. Power Transmission Control:
   These are generalizations of eddy-current (and hysteresis) clutches to include possibly multiple members with non circular/non-cylindrical geometries, transmitting force/torque using electromagnetic interactions, using ideas similar to Power Control.
3. Load Control:
   The force produced by the interaction between one or more magnets and/or induction members and/or hysteresis members, of suitable properties (Section **Error! Reference source not found.**) can be exerted at various states (positions) in the mechanism, using possibly multiple magnets and/or multiple induction/hysteresis mechanism of suitable properties (Section **Error! Reference source not found.**), and suitably located. This will lead to the mechanism load, and hence speed being modulated at these selected states, allowing arbitrary timing to be generated, even with the application of a constant driving force or torque (for simplicity, this is not necessary) to the whole mechanism. Note that the interaction between two magnets is a dissipationless force. Energy is stored in the magnetic field in unstable states of the mechanism, and returned when the mechanism moves to stable rest states.

The combination of power control, power transmission control, and load control enables new methods of designing mechanisms, to satisfy desired path, timing, and loading characteristics. *The design of the mechanism can be based on kinematic principles primarily*[1]*, with the mechanism paths (for the constrained portions) being used to develop the constraint surfaces. Timing along the mechanism paths, as well as force exerted by the mechanism on the prime mover, or to the external environment in general*, can be changed as desired at low cost, using magnetic or inductive/hysteresis force/torque applied and/or coupled at various positions, possibly in a programmable fashion.

In general, let **x(t)** represent the desired time trajectory (with multiple components representing all possible linear and angular degrees of freedom) of an arbitrary point on some link/part (member) of the mechanism. For example,

[1]Dynamic issues like force/moment balancing have also to be addressed, but can be substantially *decoupled* from the timing of the mechanism, simplifying design.

in a reciprocating mechanism, **x(t)** can be a point on a reciprocating shaft RS, of mass M. Newton's law applied to the member (RS) results in

$$x''(t) = f(x(t))/M$$

Where **f(x(t))** is the net force exerted on the member by the prime mover (we initially assume a single prime mover for simplicity) through other portions of the mechanism, and the electromagnetic load (possibly due to magnetic attraction/repulsion, and/or induction or hysteresis), at position **x(t).** In the case of rotation, we have torque instead of force, and moment of inertia instead of mass in the above equations.

.

Let us assume that Power Control, Power Transmission Control, and Load Control are all present. If, using Power Control**, fp(x(t))** is the force generated by the prime mover, and **ft((x(t))** the percentage of force transmitted through the mechanism using Power Transmission Control, including any magnetic/induction/hysteresis coupling present, and **fl(x(t))** the force due to Load Control, including any frictional losses and electromagnetic load (possibly magnetic or induction or hysteresis), we get

$$f(x(t)) = fp(x(t)) * ft(x(t)) – fl(x(t)) = M\ x''(t)$$

For a desired time trajectory **x(t),** we can find **fp(x(t)), ft(x(t))** and **fl(x(t)),** to satisfy this equation. There are clearly multiple ways this can be done.

a) Load Control Only: Here **fp(x(t))** and **ft(x(t))** are constant, or not controllable for unpowered devices. Then the amount of force required to be exerted due to Load Control is:

$$fl(x(t)) = fp(x(t))* ft(x(t)) – M\ x''(t) – ff(x(t)) \sim= fp(x(t))*ft(x(t)) - Mx''(t)$$

Where **ff(x(t))** is the frictional force, assumed to be small due to the use of bearings, etc. This force can be used to determine induction/hysteresis member geometry and/or the strengths of the magnets used, etc. One major advantage of Load Control is the lack of any stick-slip at low speeds, since both the load and force applied are much higher than the static/dynamic friction. Control using inductive/hysteresis members (not that depending on magnetic attraction/ repulsion) is dissipative.

b) Power Control Only: We have

$$fp(x(t)) = (Mx''(t) + fl(x(t)))/ft(x(t))$$

Appropriate power control can enhance mechanism energy efficiency

c) Power Transmission Control Only: We have

$$ft(x(t)) = (Mx''(t) + fl(x(t)))/fp(x(t))$$

If the structures used to implement power transmission control are similar to clutches, this has the advantage that maximum force transmittable is limited, enhancing safety.

d) Any two or all three taken together.

We note that the prescence of rest states with both multiple autonomously magnetic interacting members and hysteresis members is equivalent to energy minima being present. The presence of these energy minima (and complementary maxima) can be exploited to provide additional motion control.

Once **fp(x(t)), ft(x(t))** and **fl(x(t)),** have been determined, electromagnetic parameters of the Power Control, Power Transmission Control, and Load Control apparatus can be determined using standard techniques of electromagnetics and dynamics.

By suitably designing Power, Power Transmission, and Load Control, any desired time trajectory can be designed. For example, if **x(t)** is oscillatory without control, then an appropriate combination of controls can convert a purely sinusoidal x(t)) to one having a large number of harmonics, which is very useful in many kinds of applications e.g. vibration benches for stress testing equipment.

$$x(t) = \square\ \cos(\square\ t) \Rightarrow x(t) = \square\ \square_i \cos(\square_i t)+B_i \sin(\square_i t)]$$

An appropriate choice of controls using magnetic, and/or induction/hysteresis force changing continuously with position, can generate a broad spectrum of motion, with a close-to-continuous spectrum **X(□)**.

$$x(t) = \square \cos(\square t) \Rightarrow x(t) = \int X(\square)e^{(-j\square t)}\ d\square$$

In both these cases, the controls can also be applied in reverse, converting motion/force/torque from a multi-frequency (possibly continuous spectrum) exciting source to an motion/force/torque having a single frequency (possibly zero). This can be exemplarily applied to smooth out fluctuations from prime movers, e.g. the pulsating gas force from an internal combustion engine can be converted to a close-to-constant external force, utilizing electromagnetic attraction/repulsion and/or induction/hysteresis forces, and without necessarily using a heavy flywheell e.g,

$$x(t) = \square\ \square\ \square_i \cos(\square_i t)+B_i \sin(\square_i t)] \Rightarrow x(t) = \square \cos(\square t)$$

So far the discussion has treated a single prime mover and a single load .The generalization to multiple prime movers and multiple loads is straightforward

$$f(x(t)) = \square_i fp_i(x(t)) * ft_i(x(t)) – fl_i(x(t)) = M\ x''(t)$$

where the ith prime mover generates force $fp_i(x(t))$, which is transmitted at the rate of $ft_i(x(t))$, to the member of interest and an portion of the total load $fl_i(x(t))$ is "assigned" to this prime mover. Note that other forces like inertia/graviatational forces due to other masses, springs, etc. are assumed to be incorporated in one or more $fp_i(x(t))$'s – details are omitted for simplicity. We only note that at different positions, different prime movers can be powered, for example, only those for which the force transmission ratio is high. This can help prevent excessive internal reaction forces in the mechanism (see the Power Control discussion on page 109).

Rest states of the apparatus (if hysteresis and/or multiple autonomously magnetic interacting members are used), can be determined by determining the electromagnetic energy as a function of mechanism position, and finding the minima. Dynamics between states can be determined by solving the mechanism dynamic equations, accounting for any electromagnetic forces present. To synthesize an apparatus having given rest states, nonlinear optimization techniques can be used to determine the positioning of

hysteresis members, and/or multiple autonomously magnetic interacting members (magnets).
We have stated ((page **Error! Bookmark not defined.**):

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We further elucidate these ideas below.

Mechanisms are described in the state-of-art as composed of rigid links and connections between them (joints or pairing elements – higher or lower pairs) **Error! Reference source not found.**~~**Error! Reference source not found.**~~, **Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**. Mechanisms composed only of lower pairs are known as linkages (planar or spatial). The invention applies to mechanisms composed of lower and/or higher pairs. All the forms of the invention – Power Control, Power Transmission Control, and Load Control, can be applied to general mechanisms. We shall first describe enhancement of the mechanism's constituents, in their unpowered state (Load Control), and then discuss enhancements of traditional arrangements to Power Control and Power Transmission Control.

GENERALIZATION OF LOAD CONTROL:
The invention adds to rigid links, members either generating or interacting with magnetic flux (magnets and/or induction members and/or hysteresis members as per Section **Error! Reference source not found.**). In certain preferred embodiments, the aforesaid members can be positioned close to a joint (say J) on one link (say link 1), and interact with other members positioned close to the same joint J, on the other rigid link, to which it is joined at J (say link 2). In such cases, we use the terminology that joint J has been enhanced by the addition of the aforesaid members. When the mechanism is assembled, the mutual interaction of the aforesaid members determines rest positions and dynamics. ***There can be multiple rest positions, yielding monostables, bistables, as well as multi-valued mechanical logic***. Such mechanisms can be cascaded together to form logic functions, analogous to electronics.

ENHANCEMENT OF RIGID LINKS: The invention attaches magnets and/or induction members and/or hysteresis members as per Section **Error! Reference source not found.** to some or all of the rigid links. **Error! Reference source not found.** shows an exemplary embodiment for a rigid link R_x_300, with three revolute joints (revolute joints are well known in the state-or-art), one of which is J_x_320. Link R_x_300 is enhanced with one magnet assembly M_x_100 in the middle, and on M_x_100's left by a hysteresis member H_x_210 and on M_x_100's right by an induction member I_x_200. The electromagnetic interaction between rigid links R_x_300 and another similar but not necessarily identical link R_x_310 will partly determine mechanism rest positions (statics), and dynamics (EXAMPLE/FIG NEEDED?). Note that the number per link, shapes, sizes, position, magnetic properties of the magnet assemblies, induction/hysteresis members may differ from that shown in **Error! Reference source not found.**.

ENHANCEMENT OF JOINTS (PAIRS/PINS):
As mentioned above, in certain embodiments, the magnets/hysteresis members/induction member on one link are close to those on another link to which it is joined, in which case we say that the joint is enhanced. The invention allows enhancement of some or all the standard joints used in mechanisms with electromagnetic forces – due to attraction/repulsion and/or induction and/or hysteresis. Exemplary embodiments are shown for each one of the joints below:

1) Revolute Joint: A preferred embodiment makes the revolute joint pins and their housing magnetic (**Error! Reference source not found.**~~**Error! Reference source not found.**~~). The air-gap between the pin and the housing may or may not change as the pin rotates relative to its housing during motion of the mechanism. The magnets may be attached to circular disks attached to the pin and the housing, to obtain more torque due to the larger radius (FIGURE REQUIRED?). In general, one or more induction members, hysteresis members, multiple autonomously magnetic interacting members, magnet/induction/hysteresis members of different geometry, etc. can be attached to the pin and/or its housing as per Section **Error! Reference source not found.**.

Error! Reference source not found. (a) shows a (hollow) pin P_x_300 connected to a first link (say link1_x_310 – not shown), rotating in a housing PH_x_320 connected to another link, say link2_x_330. Note that a ball/roller bearing may be present between P_x_300 and PH_x_320. The pin P_x_300 is magnetized as shown in **Error! Reference source not found.** (b), with two North and two South Poles, while the housing has a single North and a Single South Pole (**Error! Reference source not found.** (c)). These poles **need not** be equally spaced in angle, and can be more in number than as shown. This magnetization may be realized by attaching magnetic material to the pins themselves, or making the pin of hard magnetic material, and magnetizing it, and other means well known in the art **Error! Reference source not found.Error! Reference source not found.**. Additionally, there may be an auxiliary sleeve of nonmagnetic material enclosing pin P_x_300, to prevent it from sticking to the housing due to magnetic attraction, or other means (e.g. the aforesaid bearing) of preventing excessively close physical contact between the magnets on pin P_x_300 and those on pin housing PH_x_320.

The operation of such an enhanced joint is described as follows**. Error! Reference source not found.** shows the pin and its housing in two stable states [(a) and (b)], where the north pole of the housing impinges on the south pole of the pin, and two unstable states [(c) and (d)], where the north pole of the housing is close to the north pole of the pin. All these states are offset by one-quarter revolution in this embodiment (in general the stable/unstable states may be unequally spaced). Hence in the mechanism, link1_x_310 and link2_x_330 would tend to occupy those relative positions resulting in P_x_300 and PH_x_320 occupying either positions (a) or (b). The exact positions occupied depend on other portions of the mechanism of course.

2) Prismatic Joint: An exemplary prismatic pair (sliding joint) with magnetic interaction between the first link Link1_x_300 and Link2_x_310 is shown in **Error! Reference source not found.**~~**Error! Reference source not found.**~~. A set of magnets (or assemblies as per Section **Error! Reference source not found.**) M_x_100 on Link1_x_300 interacts with another set of magnets M_x_110 on Link2_x_310, creating electromagnetic maxima and minima (rest states). The number of magnets/assemblies on M_x_100 and M_x_110 need not be the same, and these assemblies need not be equally spaced, any may occupy one or both sides of the sliding joint. All energy maxima, or rest-states need not be equally spaced, or have the same energy.

Induction and/or hysteresis members can be added to this pair, modulating the dynamics between any two states. *Reciprocating motion of frequency less than a bandwidth B depending on the strength of the induction/hysteresis, will be transmitted between Link1_x_300 and Link2_x_310. B, the 3dB bandwidth of motion transmission, can be calculated by well-known techniques of electromagnetics and dynamics*.

1) SCREW PAIRS, CYLINDRICAL PAIRS, SPHERIC PAIR, PLANAR PAIRS, HIGHER PAIRS: The invention similarly enhances these pairs with magnets and/or induction and/or hysteresis members.
    a) Screw Pair: The exemplary screw mechanism in **Error! Reference source not found.** converting rotary motion into translatory motion and vice versa (in some cases) can exhibit rest-states, possibly non-uniformly spaced, either in angle or linear position along the screw, and arbitrary customizable dynamics between one state and another through the use of one or more magnets and/or induction and /or hysteresis members attached to either or both of the screw or the nut follower. Specifically, the rest states of nut N_x_310 are determined by the interaction of magnets M_x_100, M_x_110 (attached to Screw SH_x_300), and M_x_120, M_x_130 (attached to nut N_x_310 by means not shown), and dynamics between these states determined by a combination of the aforesaid magnetic interaction and induction forces induced in I_x_200 interacting with the above mentioned magnets.
    b) Cylindrical Pair: This can be regarded as a combination of revolute and prismatic pairs, with both translation and rotational motion, and the same considerations apply.
    c) Spherical Pair: This is a generalization of revolute pairs to 3-dimensions. Rest states can be arranged at arbitrary azimuth and altitude angles, and dynamics between one state and another can be controlled using one or magnets and/or induction and/or hysteresis members.
    d) Planar Pair: The carom board (page **Error! Bookmark not defined.**) is an example of a planar pair, where the striker and pieces (constituting the first rigid link) can move only on the board surface (constituting the second link). Enhancement of the board and/or striker and/or pieces with magnets and/or induction and/or hysteresis members as per Section **Error! Reference source not found.** enables the customization of apparatus rest positions and/or dynamics.
    e) Higher Pairs: The pieces in billiards and snooker have a point contact between one member and the board surface, and the same enhancements as the planar pair apply.

In mechanisms constructed according to the invention, some or all of the links and/or joints can be thus enhanced. *It is not necessary that all joints or even all joints of a certain type be enhanced in the same manner*. The **interaction** of all the magnetic and/or hysteresis forces will determine the rest position of the apparatus. The sizes of these forces can be controlled by suitable design and magnetizations of the magnets, induction, and hysteresis members, on the links and the two constituents of some or all joints (pin and its housing for a revolute joint), as per Section **Error! Reference source not found.**. Suitable design and orientation of such magnetized links and joints can be used to realize any desired rest-positions of the mechanism. If there are K desired rest positions for the apparatus, then the magnets in the pairs/joints will have O(K) poles.

- In an exemplary design for a mechanism with one degree of freedom, with only revolute joints (pins and housings), only one pin is magnetized with K North-south pole pairs, the housing has a single N-S pair, and the rest are non-magnetic. A simple algorithm to determine the pole locations is to place a N-S pair on the pin, aligned with the S-N field on the housing in each desired rest-state. In general, the resulting N-S pairs may be close together, in which case, multiple pins can be magnetized, with each pin having rest-positions at a subset of the rest-states of the whole mechanism. *The selection of these subsets can be made in a manner as to optimize criteria such as maximizing holding force, positioning accuracy, etc. Exemplarily, to maximize positioning accuracy of any point on a link of the mechanism, the pin most sensitive to changes in the aforesaid point's position can exemplarily have a rest-state corresponding to each desired location of the aforesaid point*. Multiple pins/housings may be magnetized at the same desired locations, possibly yielding higher holding forces, for both single-degree of freedom mechanisms, and multiple-degree of freedom mechanism. The number of N-S pairs in each pin/housing may in general differ.
- In general, dynamic motion between two states can be controlled by any of the variants using possibly induction/hysteresis effects, multiple au-

tonomously magnetic interacting members, induction/hysteresis members of different geometry, etc. as per Section **Error! Reference source not found.**. Exemplarily, these forces can be used to slow down "ratcheting" between states – e.g. the ejector/latch **Error! Bookmark not defined.**.

Connecting links and joints/pairs enhanced in the aforesaid manner as per the invention, enables creation of mechanisms of arbitrary complexity ranging from 4-bar linkages and its variants (including quick-return mechanisms), Geneva Mechanisms, the Watt Chain, the Stephenson Chain**Error! Reference source not found.**, Chebychev's walking mechanism**Error! Reference source not found.** (exemplarily, here the rest states can be designed to fold the legs in a crouching position) etc. *An advantage of this invention is that the motion between the states is noiseless, unlike ratcheting alternatives well known in the state of art.*

GENERALIZATION OF POWER CONTROL: From one point of view, the invention is a generalization of well-known stepper motors, to create stepper mechanisms (especially if there are powered coils in addition to permanent magnets on the pins)[2].

Error! Reference source not found. shows an exemplary three-link mechanism (this is actually a 4-bar linkage with one infinite link) composed of rigid links R_x_300, R_x_310, R_x_320, with a revolute joint J_x_400 connecting R_x_300 and R_x_310, another revolute joint connecting R_x_310 and R_x_320, and a prismatic joint J_x_410 connecting R_x_300 and R_x_320. Some or all joints are enhanced as per the invention, with magnets and/or hysteresis and/or induction members, possibly with varying shapes, sizes, materials, texture, etc. as per Section **Error! Reference source not found.**. In addition, magnet M_x_100 and induction member I_x_200 interact to produce an inductive braking force.

Powered coils PC_x_330 and PC_x_340 cause motion at joint J_x_400 and powered coils PC_x_350 and PC_x_360 cause motion at joint J_x_410 (the coils can be on more than one link in general, and are constructed with ferromagnetic cores, etc as is well known in the state-of-art). The flux produced by the aforesaid powered coils can vary with angular position of J_x_400 and linear position of J_x_410, similar to discussion on motors with an ellipsoidal rotor (Section **Error! Reference source not found.**). An appropriate design of the joints (position, number and energy level of the rest-states, etc), together with sequencing and control of the electrical excitation to the aforesaid coils from control circuitry CP_x_500, will make the mechanism step between states, exactly analogous to stepper motors taking steps.

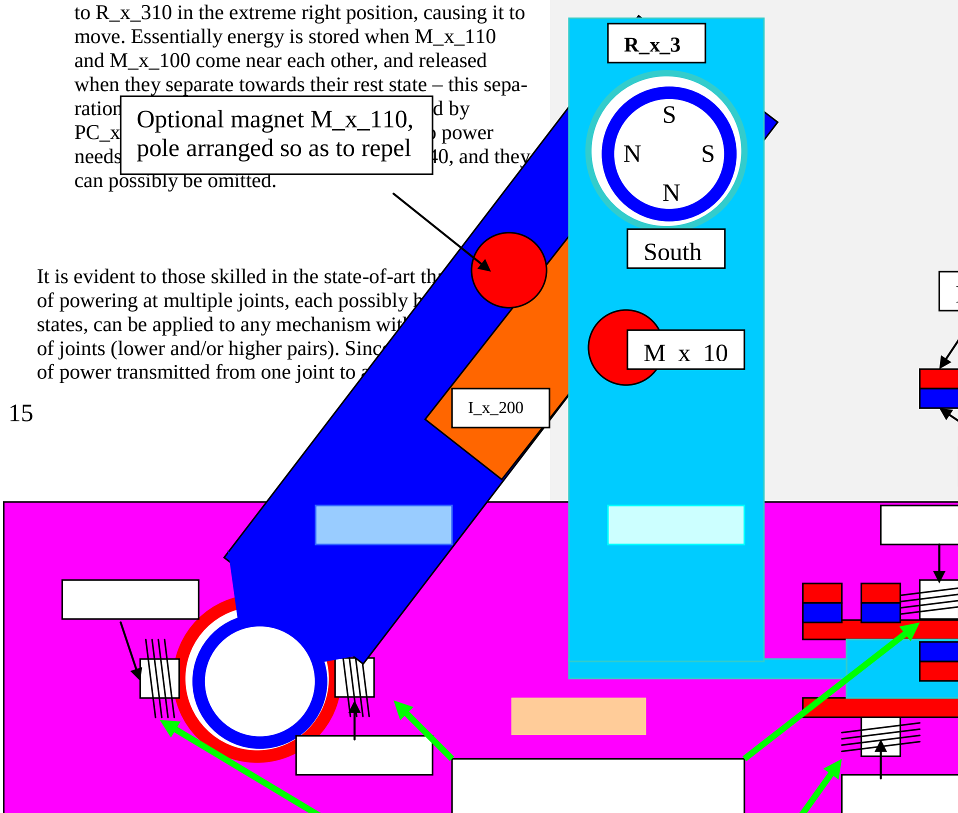
The invention distinguishes itself from the state-of-art in several ways.

a) In **Error! Reference source not found.**, the set of links forms a closed loop, the amplitude and sequencing of the excitation to the different joints has to be chosen to generally (but not always) to avoid opposing each other. This is unlike kinematically chained powered robotic arms, where the excitation to the different actuators can be substantially independent Error! Reference source not found.~~Error! Reference source not found.~~, Error! Reference source not found.~~Error! Reference source not found.~~, **Error! Reference source not found.**, **Error! Reference source not found.**, **Error! Reference source not found.**, the only constraint being the desired path of the kinematic chain.

b) In addition, the set of powered coils PC_x_330, PC_x_340, PC_x_350, PC_x_360 **need not form the windings for one complete rotary motor and one complete linear motor**, but are placed so as to optimize a desired criterion, e.g. power delivery, fineness of control, etc. If power delivery is the criterion, coils PC_x_350 and PC_x_360 are placed and controlled *so as to apply force in the middle of the travel of prismatic joint* J_x_410, since the mechanism cannot be moved by a linear force, when rigid link R_x_310 is exactly in line with R_x_320 and joint J_x_410 (this happens at extremeties of travel). Even if the mechanism does not allow R_x_310 to perfectly align with R_x_320, the effectiveness of the linear force is reduced at the extremeties of travel of J_x_410. *Powered coils PC_x_330 and PC_x_340 are placed and controlled to apply force at those positions of revolute joint J_x_400, which corresponds to the mechanism having prismatic joint J_x_410 at its extremeties*, so as to compensate the lack of drive from PC_x_350 and PC_x_360. They can be unpowered, or designed to not apply any force/torque at other states of revolute joint J_x_400. This control can be driven by the mechanism's motion itself, opening and/or closing switches, generalizing the action of commutators in electric motors. Essentially the apparatus of **Error! Reference source not found.** is a "hybrid rotary-linear motor" and all powered coils and flux paths have to be jointly optimized.

c) A variant of this apparatus uses another magnet M_x_110 arranged so as to repel M_x_100 near its extreme right position. This provides a sideways force to R_x_310 in the extreme right position, causing it to move. Essentially energy is stored when M_x_110 and M_x_100 come near each other, and released when they separate towards their rest state – this separation ... d by PC_x ... power needs ... 0, and they can possibly be omitted.

It is evident to those skilled in the state-of-art th... of powering at multiple joints, each possibly b... states, can be applied to any mechanism wi... of joints (lower and/or higher pairs). Sinc... of power transmitted from one joint to a...



[2] Changing the coil excitation "steps" the mechanism through its different rest-states, which can be chosen to be on an appropriate possibly non-uniform grid for one or more points in the mechanism.

ness of motion control, etc. varies depending on the state of the mechanism (this dependence on the position function is well known in the state-of-art of mechanisms), the joints and their powered coils can be so selected and powered in sequence to respectively maximize the power transmitted to the output in all positions, improve fineness of control, etc. Exemplarily, states where no power is transmitted to the output can be eliminated ("so called dwell states"). In addition, the ability to selectively power different joints allows us to reduce peak forces and associated stresses internal to the mechanism. This flexibility can minimize heavy reaction forces from the constraint surfaces, caused by actuation from a powered coil at a joint/link whose force is minimally transmitted to the output link, in the current mechanism state.

All sections should be numbered as shown above in the section heading. The section headings should be in Times New Roman, size 14, and bold typeface. Capitalize the first letters of each word in the section heading except prepositions such as "of", "on", "for", etc.

Do not indent the first line of the first paragraph in a section or a sub-section. Indent the first line of a new paragraph by 0.635 cm (0.25″) from the left margin.

The text of the body of the paper should be in Times New Roman with size equal to 10.

The first section should provide the background to the subject matter of the paper. It should not occupy more than 25% of the paper.

1.1 Sub-section heading

Sub-sections headings should be numbered as shown above. They should be in Times New Roman, size 12, and bold typeface.

1.1.1 Sub-section heading

The sub-section heading should be in Times New Roman, size 10, and bold. The sub-sections should be numbered as shown above.

1.2 Margins and spacing

The paper size is A4. The left margin should be 2.22 cm (0.875″), the right 1.40 cm (0.552″), the top 2.54 cm (1″), and the bottom 1.902 cm (0.75″). The title and the authors' names and affiliations should be spread across the entire page as shown above. However, the body of the paper should be in two columns. The spacing between the left and the right columns should be 0.635 cm (0.25″). Both columns should be of the same width.

The text in the entire paper, including that in the abstract, should be single-spaced. There should be 3 pt spacing before each paragraph but zero space below. The headings and all subheadings should have 13 pt spacing above and below.

Figures and Tables should have 13 pt space above and 6 pt space below.

1.2.1 Header and footer

Do not change the paper number "###" in "NaCoMM-2007-###" in the top corner of the header region. Retain the page number in the footer.

2 Equations

The equations are to typed using the Equation Editor in Word or by using MathType. The size should be set to 10. All vectors. matrices, and tensors should be in bold type. The equations should be centered with a right tap for the equation number as shown below.

$$\sin^2\theta + \cos^2\theta = 1 \tag{1}$$

$$\mathbf{K}_t\mathbf{u} = \Delta\mathbf{f}_{\text{ext}} \tag{2}$$

$$\mathbf{E}_{ij} = \mathbf{e}_i \otimes \mathbf{e}_j \tag{3}$$

The equations are to be referred to as Eq. (#) in the text. For example, Eq. (1) is a consequence of the Pythagoras theorem.

1. A Detailed Example: Flywheel of an IC Engine.

3 Figures and Tables

The figures and tables should be centered. The figure caption should be placed below the figure as shown in Fig. (1). Figures should be cited in the text as done in the previous sentence. Care should be taken to make the figure captions as clear as possible. Multiple sentences are encouraged in the figure caption. An example is shown in Fig. (1).

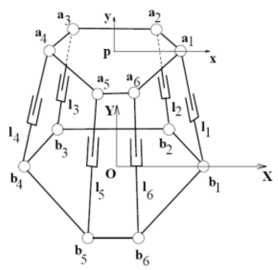


Figure 1: The semi-regular Stewart platform manipulator. It has six actuators. The positions of the ball joints are labeled and global and local coordinate systems are marked.

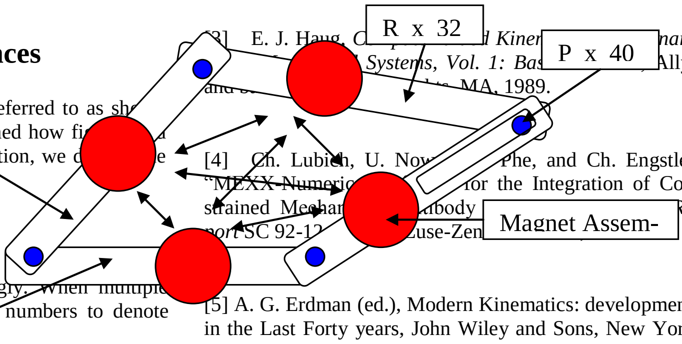
Tables are to be formatted as shown in Table 1. Table captions should be placed at the top. Tables should be cited in the text as shown in the first sentence of this paragraph.

Table 1: Some parameters related to planar revolute joint

S. No.	*Parameters*	*Range*
1	α_1, L_1	$0 \leq \alpha_1 \leq \pi$

2	β_1, L_2	$0 \le \beta_1 \le \pi$
3	γ_1, L_3	$0 \le \gamma_1 \le \pi$

4 Footnotes and References



Sections and sub-sections should be referred to as sh[illegible] in the next sentence. Section 3 explained how fi[illegible] tables should be form[illegible]ection, we d[illegible]e formatting of footnotes [illegible]s.

4.1 Footnotes

The footnotes should be used sparingly. [illegible] footnotes are used, u[illegible]ed numbers to denote them.[3]

4.2 References

References should be numbered in the order of their first occurrence. They should be cited with “[#]” at the end of the sentence or in the middle as the case may be. The citations should be listed at the end of the paper but before the Appendix, if any. The format of the citations is given in the section entitled “References” at the end of the paper. Different types of references , including conference proceedings, journal paper, book, technical report, edited book, etc., are indicated.

5 Conclusions

The formatting rules for the NaCoMM07 paper are outlined in this document. The cooperation of all the authors is appreciated in producing the conference proceedings of high quality.

Acknowledgment

Keep the acknowledgment short and sweet. An example is here: “we thank Prof. Guruprakash for allowing us to use his experimental facilities.”

References

[1] W. W. Armstrong, “Recursive Solution to the Equations of Motion in an n-link Manipulator,” *Proc. Fifth World Congress on Theory of Machines and Mechanisms, Montreal*, 1979.

[2] D. S. Bae and E. J. Haug, “A Recursive Formulation for Constrained Mechanical Systems Dynamics: Part I. Open Loop Systems,” *Mechanics of Structures and Machines*, Vol. 15, No. 3, 1987, pp. 359-382.

[3] E. J. Haug, *C[illegible] Kiner[illegible]nam-[illegible] Systems, Vol. 1: Bas[illegible]*, Allyn and [illegible] MA, 1989.

[4] Ch. Lubich, U. Now[illegible]he, and Ch. Engstler, “MEXX-Numeric[illegible] for the Integration of Constrained Mechan[illegible]body [illegible] *Report* SC 92-12[illegible]use-Zen[illegible]

[5] A. G. Erdman (ed.), Modern Kinematics: developments in the Last Forty years, John Wiley and Sons, New York, 1993.

Appendix

A Real Linear Maps and Geometry of the Range Space

Let us consider the real linear map shown below. It has eigenvalues and eigenvectors.

$$f : \Re^n \to \Re^n \tag{A1}$$

A.1 Singular linear maps

One of its eigenvalues is zero.

Appendix: Energy Levels and Forces offered by High Powered Magnetics

Below, we illustrate the potential of high-power rare-earth magnets, for motion control. We begin by discussing the energy levels available, follow up with a discussion of forces and damping constants available. In general, modern high power magnets are approaching energy levels offered by low end pneumatic systems, while being more flexible and cost-effective.

Energy Levels

The energy stored per unit volume in a field of B Teslas, in a unit permeability substance is given by:

$E_m = ½\ \mu_0\ B^2 = ½ * 1/(4*\pi * 10^{-7}) * 0.5^2 = 100$ KJ/m^3 at 0.5T

[3] Footnote numbers should continue throughout the article.

For fields varying between 0.5 to 1T, the stored energy varies from 100 KJ/m^3 to 400 KJ/m^3.Such fields are easily generated using commonly available (N35 or N45) Neodymium-Iron-Boron magnets (N45 is about 15-20% more energy dense than the N35). Variants of N35/N45 are available, with maximum operating temperatures of 80 to 150 degrees C.

In comparison, for pneumatic systems, one formula for stored energy per unit volume, at pressure P_1 working isothermally against standard atmosphere P_2 is:

$$E_p = P_1 * \ln(P_1/P_2) = 1\text{MPa} * \ln(1\text{MPa}/0.1\text{ MPa}) = 805\text{ KJ/m}^3 \text{ at } 0{,}5\text{Mpa}$$

We note that high speed expansions are polytropic (closer to adiabatic) instead of isothermal, resulting in lowered energy densities. For polytropic expansion ($PV^{\gamma}=C$), we have

$$E_p = P_1/(\gamma-1)*(1-(P_2/P_1)^{(\gamma-1)/\gamma})$$

$$2.5*P_1*(1-(P_2/P_1)^{2/7})=461\text{ KJ/m}^3 \text{ at } 0{,}5\text{Mpa}, \gamma=1.4=7/5 \text{ (adiabatic)}$$

$$1.5*P_1*(1-(P_2/P_1)^{2/5})=356\text{ KJ/m}^3 \text{ at } 0{,}5\text{Mpa}, \gamma=5/3$$

For pressures varying between 0.5 to 1 MPa, the stored isothermal (adiabatic) energy varies from 800 KJ/m^3 to 2300 KJ/m^3 (1200 KJ/m^3), about 2 to 6 times magnetic energy levels at 0.7 Tesla (see the detail in Table 3~~Table 3~~). We note that Firestone air springs are typically rated at 100 PSI, 1300 KJ/m^3 isothermal, 750 KJ/ m^3 adiabatic, about 4 times the magnetic energy at 0.7 T.

B (Tesla)	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Emag(KJ/m^3)	15.92	35.81	63.66	99.47	143.24	194.96	254.65	322.29	397.89
P(Pa) down	Ratio of Magnetic to Pnuematic Energies								
200000	17.7%	39.9%	70.9%	110.7%	159.5%	217.0%	283.5%	358.8%	442.9%
300000	7.9%	17.7%	31.5%	49.2%	70.9%	96.5%	126.0%	159.5%	196.9%
400000	4.9%	10.9%	19.5%	30.4%	43.8%	59.6%	77.9%	98.5%	121.7%
500000	3.5%	7.8%	13.8%	21.6%	31.1%	42.3%	55.3%	69.9%	86.4%
600000	2.6%	6.0%	10.6%	16.6%	23.8%	32.4%	42.4%	53.6%	66.2%
700000	2.1%	4.8%	8.5%	13.3%	19.2%	26.1%	34.1%	43.2%	53.3%
800000	1.8%	4.0%	7.1%	11.1%	16.0%	21.8%	28.4%	36.0%	44.4%
900000	1.5%	3.4%	6.1%	9.5%	13.7%	18.6%	24.3%	30.7%	37.9%
1000000	1.3%	3.0%	5.3%	8.3%	11.9%	16.2%	21.1%	26.7%	33.0%

Table 3 Ratio of Magnetic to Pneumatic Energies as a function of field strength and Pressure. Areas of magnetic dominance shown in green

However, magnetic energy storage using permanent magnets has the following advantages:

1. It is passive, requiring no power (no compressors).
2. The stored energy density, and its gradient can be customized as a function of position, resulting in position dependent energy/force profiles, designed to match system dynamics,
3. Customization of the energy density can be achieved by appropriate dimensions and geometries of the magnetic/induction members. The energy density can also be changed by relatively small motion (linear/angular) of magnets.
4. Electrical modulation of magnetic fields can be done at high speed, offering high speed motion/force control.

Magnetic motion/force control techniques are hence a potential replacement for low power pneumatic systems, and a promising adjunct to high power pneumatics. They can also be used for any application where lossless energy storage and/or dissipation is useful, e.g., in torque smoothing for engines, using a magnetic flywheel whose effective moment of inertia can be made to vary over a cycle of revolution.

Forces due to Magnetic Attraction/Repulsion

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Maglev technology has relied on the high energy densities and associated forces produced by typically superconducting magnets for decades **Error! Reference source not found.**. The advent of high power rare earth magnets has made this technology cost effective for many other applications, including automotive. Since the magnetic forces depend strongly on the relative position of interacting magnets, very high spring constants, which can be *customized easily* by changing the dimensions, geometry, and/or relative position of one or more magnets can be obtained. This enables highly effective perturbation reduction, even for large scale road disturbances. Active control can be used to stabilize the often positionally unstable magnet and attached suspension system.

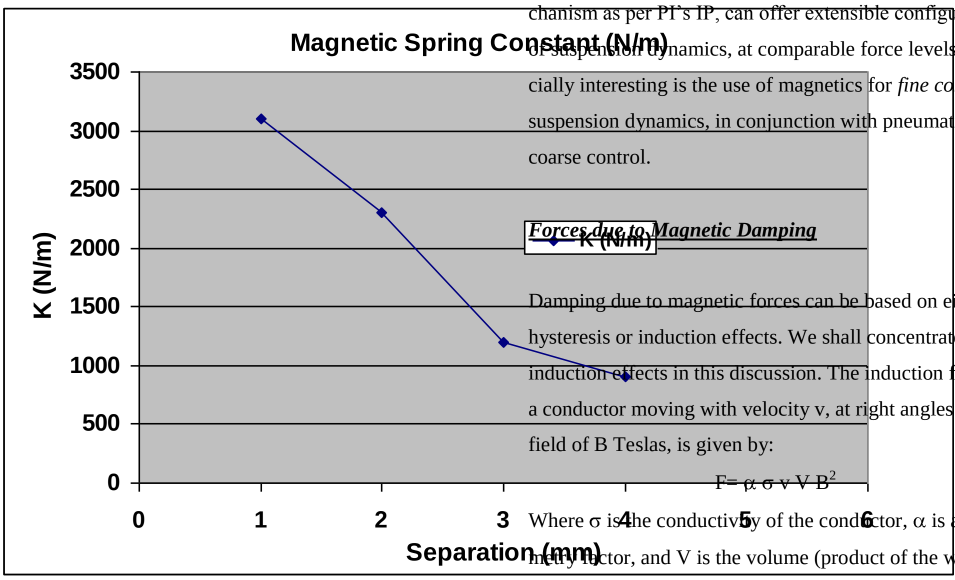

Figure 17: Magnetic Spring Constant 1cmx1cmx1cm magnets arranged to repel each other

Figure 17~~Figure 16~~ shows the spring constant obtained from the repulsive force between two small N35 Neodymium magnets 1cm x 1cm x 1cm in size. FEM analysis was used to obtain this force. Figure 17~~Figure 16~~ shows that dramatic changes in spring constant from 3100 N/m to 900 N/m can be obtained with very small changes (5-10 mm) in relative positioning, facilitating road disturbance rejection using active control of spring constants. The higher magnetic strength N45 has about 15-20% higher energy/force levels.

In contrast, a Firestone air-spring 1T14C-1 has a payload of 3600 lbs, and a design position of 6.5", yielding a spring constant of 100,000 N/m. This force level is achievable using between 60 to 200 1cc Neodymium magnets appropriately arranged. A configuration where all the magnets are lumped to form two 10 cm x 10 cm blocks (*with careful attention to shielding*[4]) offers a potential replacement for the Firestone air-spring. A configuration where all the magnets are distributed throughout the suspension mechanism as per PI's IP, can offer extensible configuration of suspension dynamics, at comparable force levels. Especially interesting is the use of magnetics for *fine control* of suspension dynamics, in conjunction with pneumatics for coarse control.

Forces due to Magnetic Damping

Damping due to magnetic forces can be based on either hysteresis or induction effects. We shall concentrate on induction effects in this discussion. The induction force on a conductor moving with velocity v, at right angles to a field of B Teslas, is given by:

$$F = \alpha\, \sigma\, v\, V\, B^2$$

Where σ is the conductivity of the conductor, α is a geometry factor, and V is the volume (product of the width, length and thickness) of the region of interaction between the conductor and the field. This equation holds for velocities small enough for the induced field to be neglected. Since the energy density is given by

$$E_m = \frac{1}{2}\, \mu_0\, B^2$$

The force equation may be rewritten as

$$F = 2\, \alpha\, \mu_0\, \sigma\, v\, V\, E_m$$

Note that in addition to the energy density E_m, the conductivity σ, and the geometry factor α also determine the force. The damping coefficient (Force/Velocity) for Copper turns out to be

$$F/v = 145\, \alpha\, E_m\, V$$

This yields damping densities of 15 N/(m/s) per cubic centimeter, at 0.5 Tesla. Note that the presence of both the geometry and the volume factors shows that the damping coefficient can be easily changed as a function of position, by changing the physical dimensions, geometry, and relative orientation of the conductors and magnets involved. Damping using pneumatics requires active exhaust control – intrinsic damping is negligible for air unless turbulent flow regimes are excited.

[4] This is a very large magnet, and would not typically be used in one piece

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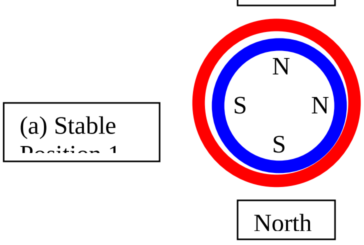

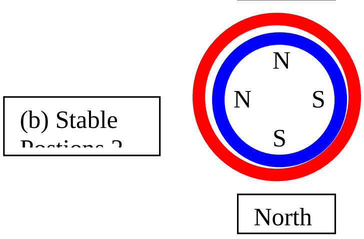

These issues are summarized in Table 4~~Table 4~~, which provides a comparison of several alternatives for damping. The damping coefficient obtainable using inductive effects is in the 8 N/(m/s) range for a unit 1 cm x 1 cm x 0.5 damper, inducing forces in a copper induction member 1mm in thickness. The use of multiple-magnets, thicker induction pieces, and mechanical advantage can raise this to the 1-4 KN/(m/s) range, adequate for automotive applications (e.g. a small car in **Error! Reference source not found.**, **Error! Reference source not found.**~~**Error! Reference source not found.**~~). Note that electromagnets are not cost-effective – requiring 100 times the volume, and dissipating an order of magnitude more power in resistive losses alone, than passive rare earths. They can be used in conjunction with rare earths, for high-speed fine damping control.

Table 4: Comparison of Various Active and Passive Control methodologies: Numbers based on per unit magnetic components

	Peak Velocity	Peak Force	Peak Coefficient	Speed	Size of Principal Element	Power Control	Power Dissip	Power Gain	Remarks
Passive Rare Earth	80 cm/s	6N	8 N/(m/s)	50 Hz	0.5 cc	5.5W	2.8W	2	Unit
Electromagn.	80 cm/s	6N	8 N/(m/s)	>50Hz	4-60cc	5.5W	20W	0.2	Requires Power
Pneumatic	Very High?		Pressure Change Dependent	50 Hz (too high?)	2.5 mm		1.2W		Damping Due to Active Exhaust Control
Hydraulic				20Hz?					Slow response

The use of magnetic rather than pneumatic or hydraulic systems, in addition, offers significant benefits as outlined below:

- High damping forces, without requiring active exhaust control as in pneumatics.
- Higher Speed (responses in 10's milliseconds), especially compared with hydraulics.
- Easy customizability of the force-velocity profile as a function of position.
- Reduced number of moving parts compared to air-suspension systems with regulators.
- Reduced Noise
- Control Power gains superior to the best air-suspension systems (better than the estimates of x5 based on reported data for Firestone **Error! Reference source not found.**).

In a Lagrangian formulation, we have

$$L(q,q')=K.E - P.E$$

and we have

$$\frac{d}{dt}\frac{\partial L}{\partial \dot{q}} - \frac{\partial T}{\partial q} = Q$$

as the equations of motion in terms of the generalized co-ordinate q.

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Comment [P1]: Based on maximum induced field being limited – system will work beyond this