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. *This geometry incorporates intelligence about the desired dynamical behavior of the system by incorporating appropriate internal electromagnetic forces to optimize the dynamics presented to the external world.* The ideas can be used with either 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 [Uicker-Pennock-Shigley -[2], Ghosh-Malik [3], Ghosal [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 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 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).

Dynamics can be partially decoupled from kinematics through incorporation of auxiliary forces (due to gravity, electromagnetics,) at various states in the mechanism, thus changing the dynamics, keeping the kinematics invariant. While gravitational forces cannot be conveniently controlled, springs, pneumatics, hydraulics, etc can be used as controllable reservoirs of force, but typically cannot operate at high speeds due to inbuilt inertia, require expensive sealing, etc.

Electromagnetic forces however, are high speed, predictable, repeatable, and non-contact eliminating wear and tear issues. Losses in electromagnetic systems can be controlled through laminations, proper materials, etc. Till recently, however, electromagnetic forces were 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 (Campbell [5]), 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 are designed to optimize mechanism dynamics.

This paper discusses the architecture of emecs, and illustrates their capabilities in important applications. Methods to design these emecs to achieve desired goals are the topic of separate papers. Since high power magnets are a critical enabler of emecs, we first discuss the capabilities of modern rare earth magnets (Section 2). Then we discuss how such magnets can be used to create enhanced pairs (*epairs* - Section 4), which are the building blocks of emecs (Section 3, 5). The architecture of emecs based on enhanced pairs follows. Finally, a number of applications of emecs are discussed (Section 6, 7).

Emecs can be used in conjunction with other methods including gravity, springs, electromagnetic forces due to magnets, hysteresis/induction loads, etc. Emecs can be applied to mechanisms incorporating lever arms, gears etc, with well known methods for design (Uicker, Pennock & Shigley [2], Ghosh & Mallick [3], Ghosal [1], Myszka [4]).

2. Capabilities of Modern Rare Earth Magnets

We begin by discussing the energy levels available using modern rare earth magnets, and 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 ([5]) is given by:

$E_m = ½\ 1/\mu_0\ B^2 = ½ * 1/(4*\pi * 10^{-7}) * 0.5^2 = 100$ KJ/m^3 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 compares magnetic energy levels with those produced by different kinds of forces, under comparable conditions.

In Table 1 the maximum obtainable electric field energy per unit volume is limited by breakdown in air [6]

$E = ½*\varepsilon*E_{BV}^2$

where E_{BV} is the breakdown voltage, 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 kinetic energy, the choice of 10 m/s as the reference speed was based on sizes and speeds of common mechanisms.

For pneumatics, the stored energy per unit volume, at pressure P_1 working isothermally against standard atmosphere P_2 ([2],[3]) is:

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

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

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

Barring high pressure pneumatics (and very high speed mechanisms where K.E dominates), the magnetic field energy is the highest per unit volume. Since magnetics does not require mechanisms to handle high pressure air, and can be miniaturized, 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 (which are the energy gradients) exerted by them. Since these 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.

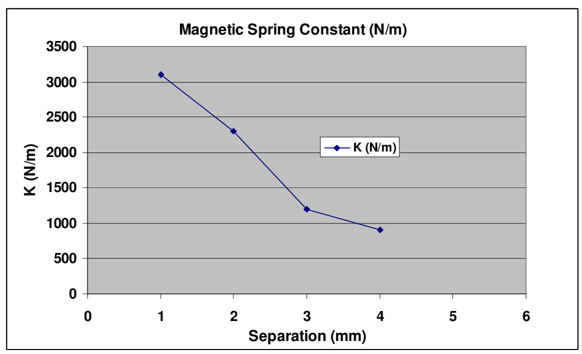


Figure 1: Magnetic Spring Constant 1cmx1cmx1cm magnets arranged to repel each other

Figure 1 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 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 (see Haus-Melcher [7]):
$F = \alpha \sigma v V B^2$

Where σ is the conductivity of the conductor (5.9×10^7 for copper), 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

$$\underline{E}_m = \tfrac{1}{2} \underline{\mu}_0 B^2$$

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 relative to stored kinetic energy (for copper) is clearly

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

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

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

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)

An electrical motor or generator (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, - the stator-rotor system for rotating machines, and the track-follower system for linear machines.

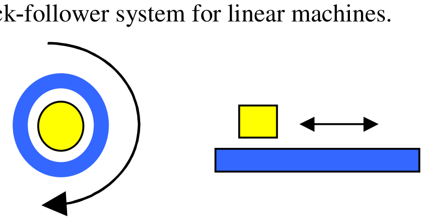


Figure 2 Rotary and Linear Motors

When used to power a mechanism (e.g. a robot manipulator), these motors actuate one or more pairs, and are jointly controlled, as shown in 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, and has to deal with the varying input-output behaviour exhibited by the mechanism (varying condition numbers and/or singularities of the relevant Jacobians, loss/gain of degrees of freedom, etc).

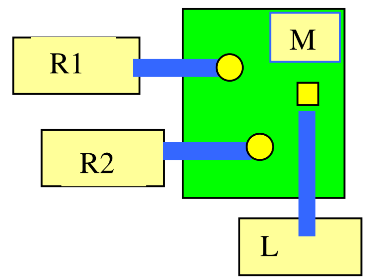


Figure 3 Mechanism driven by two rotary and one linear motor

Our 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 [10], [11]. Rather, *the different portions of the motor, and associated electromagnetic interactions 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 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 – but modern rare earths are quite stable.
- The mechanism becomes a special purpose machine, but can be cost-effectively manufactured using modern CAD/CAM.

4. EPAIRS: 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 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. Damping constants of around 15 N/(m/s) can be obtained with small magnets (Section 2).

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 *emec*. The enhanced pair will be referred to as an *epair*.

i. Type A: Interaction Localized at Joints: Mechanisms can have electromagnetic interactions at the joints only (we shall primarily discuss these).

In general, a pair which is enhanced 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 (Figure 10 shows magnetized links interacting). Analysis requires solutions to electrodynamic equations, under mechanism constraints.

Enhanced Revolute Pairs: Analysis and Optimization:

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 lossless storage/release of energy, while the conductors/magnetic materials provide damping. *The key difference between installing a motor at this joint 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 (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 (b), unlike poles of the rotor and stator 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).

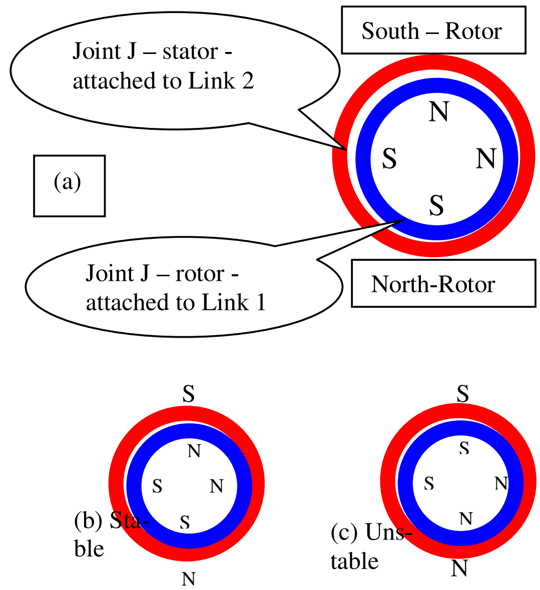


Figure 4: Electromagnetic interactions confined to the joints – Enhanced Revolute Pair

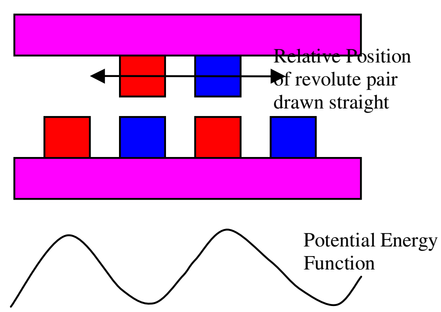
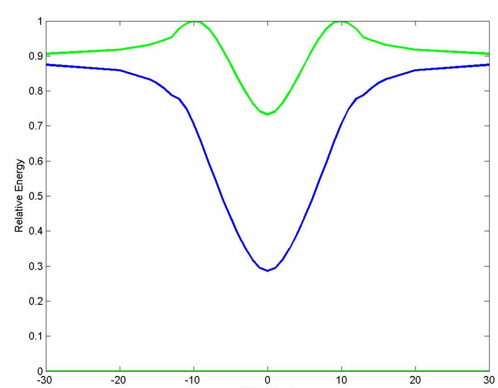


Figure 5: Energy Function of Revolute Pair drawn straight with rectangular poles.



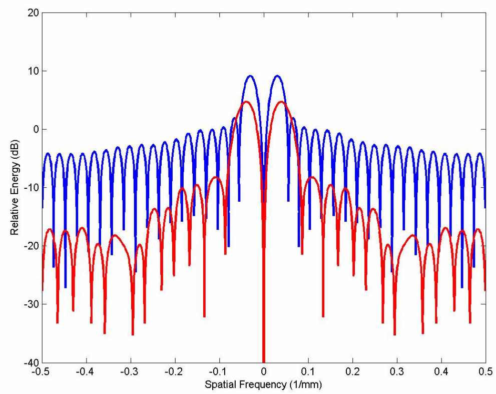


Figure 6: (a) Energy Well and (b) Fourier Spectrum. Red is for repulsive and Blue for attractive forces

The forces exerted by enhanced revolute pairs can be examined by analysis of the potential energy as a function of rotational angle (Figure 5). A set of alternating pole pairs on one link interacts with one or more (alternating) 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 [8] allows the determination of the optimal shape of the pole pieces for a desired energy function.

These ideas are elucidated in Figure 6. The energy function using FEM analysis for two rectangular N35 magnets (with back iron closing flux paths), 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 6 (a), and its spatial spectrum in Figure 6 (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 cycle every 30 mm, (1/(3 x magnet width)). The 3dB bandwidth is the same, 1 cycle every 30 mm. This bounds the spatial frequency resolution for the potential energy function, obtainable using magnets of this size. 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 superposed to implement any desired energy function to implement a desired dynamics.

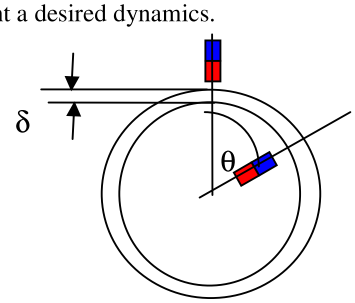


Figure 7: Torque produced by magnets

Linear superposition of fields has to be done in the force/torque and not the energy domain. Following Figure 7, 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

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

For macroscopic magnets, an integral over the pole distribution has to be carried out, using FEM techniques. The result for attraction for two 10 x 10 x 3 magnets is shown (Normalized Torque and Energy) in Figure 8 .

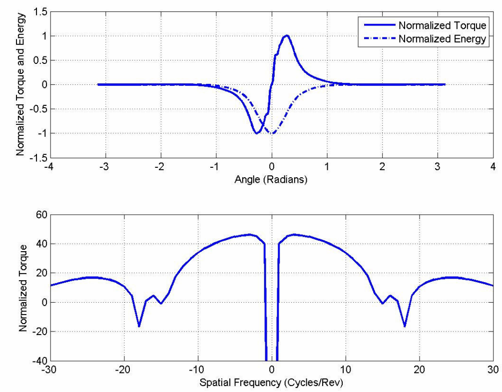


Figure 8: Torque and Energy for pole pair vs angular Separation (a) Torque/Energy versus angle (b) Spatial Spectrum of Torque (dB).

The torque integrated over the whole circumference is zero, as it must be for a passive system. The energy has a minimum when the magnets are close to each other.
The set of all torque functions $\tau(\phi)$ possible of a revolute pair with N "stator" magnets and a single "rotor" magnet, is the superposition of the elementary torques

$$\tau(\phi) = \sum_{1}^{N} \alpha_i \tau_i (\phi - \phi_i)$$

where α_i is a constant reflecting the signed strength of the magnet at position i and ϕ_i is the angular offset of the same magnet relative to the first. The strengths α_i and offsets ϕ_i are optimally chosen to synthesize a desired torque function, with minimum error. The elementary torque functions can be chosen to form a *complete orthonormal* set (other than for the constant component). This method has been used to synthesize a torque function to smooth IC engine vibrations in Section 7.

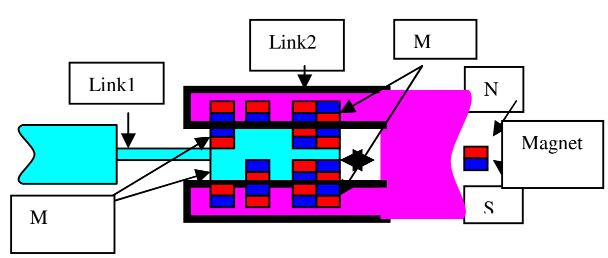


Figure 9: Prismatic Pair enhanced with magnets and/or dissipative members

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 9 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.

In general local minima (stable/unstable states) manifest themselves, creating mechanical monostables, bistables, multistables, and astables if energy is injected into the mechanism. 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.

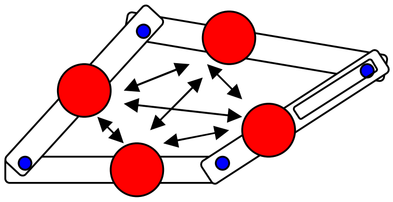


Figure 10: Distributed Electromagnetic Interactions in a 4-bar linkage

***Type B Mechanisms: Analysis and Optimization*:** 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 10).The energy function cannot be accurately separated into parts depending only on a single pair configuration, and is dependent on the global system configuration, requiring global optimization techniques.

5. EMECs: Composition of epairs

An emec is a mechanism built using links and epairs. Design of emecs can be is conceptually 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, in conjunction with kinematic constraints, as reflected in (say) 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 epairs. The multi-variate 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.

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 forces/potentials, the dynamical design becomes substantially *decoupled* from the kinematics. Simply put, where the mechanism is hard to move externally, 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 11. 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 11 (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 stable positions (steps) on a non-uniform grid, with different holding torque/forces. For pre-specified stable positions, the magnetization of A is non-uniform – and is obtained by using inverse kinematics operating on the pre-specified stable positions..
- The stepper in Figure 11 (a) exhibits singularity. 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 11 (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 [1], Nakamura [5]). We have the holding force equation

$$F(q) = K_1(q)\, FA(q) + K_2(q)\, FD(q)$$

Where $K_1(q)$ and $K_2(q)$ are the force/torque transmission matrices from A and D to C, in configuration q. FA(q) and FD(q) are the holding force/torque of the enhanced joints (epairs) at A and D respectively. For facilitating construction, the L_∞ norm can be used - then the maximum field strengths at each enhanced joint are limited. The configurations of (c) (3 epairs) and (d) (4 epairs) further extend this idea. Figure 11 (e), (f), (g) and (h) extend these ideas to actuation, with (f), (g) and (h) being singularity free.

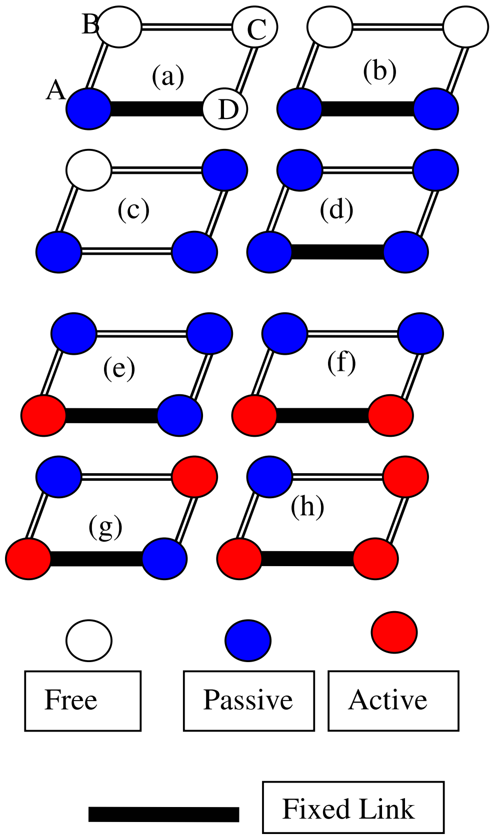


Figure 11: 4R mechanism enhanced with magnets

In passing, we briefly summarize basic design principles of emecs. If emec design is done on an energy basis, the total 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.

$P.E.(q_1,q_2,q_3,\ldots)= \Sigma\, P.E_i\,(q_1,q_2,q_3) = \Sigma \int ½\, \mu\, B_i^2\, dV$ – (1)

$K(q_1,q_2,q_3,\ldots) = \Sigma\, K_i\,(q_1,q_2,q_3) = \Sigma \int ½\, \alpha_i\, \sigma_i\, B_i^2\, dV$

This expression can be written for both Type A (local interactions) and Type B emecs (global interactions), since all terms are dependent on the entire system configuration.

We have used the fact that the potential energy per unit volume is given by $½\, \mu\, B^2$, 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). The total P.E. and K.E. is derived from desired mechanism dynamics.

For type A emecs, we have $P.E_i\,(q_1,q_2,q_3,\ldots) = P.E_i\,(q_i)$, since the epair interactions are decoupled. Hence design begins with a decomposition of the P.E. and K functions into portions implementable on separate pairs, and is analogous to 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). In general any criterion which improves dynamics can be used. If a Fourier expansion is used, we have:

$$\int ½\, \mu\, B_i^2\,(q_i)\, dV = A \cos(2\,\pi\, N\, q_i + \phi_i)$$

where there are N pole pairs in one pair member and a single pair on the other (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, strength and orientation of poles on each joint (pair) can be optimized – see the detailed example in Section 7.

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.

For type B mechanisms, the P.E/K. cannot be decoupled and global optimization techniques are used to optimize the P.E. /K functions taking the electrodynamics of the mechanism as a whole. Details are in other papers.

6. Electromagnetic CAM

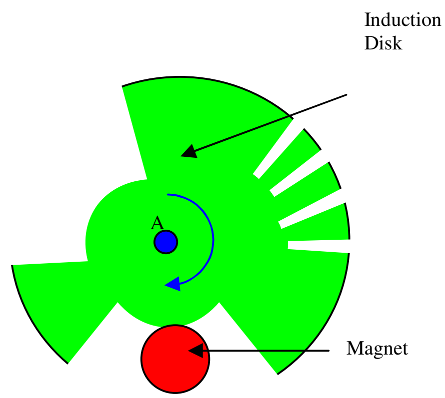


Figure 12: A non-uniform timing electromagnetic revolving cam

In this and the next section, we present a few examples of mechanisms which illustrate the power of our ideas. Figure 12 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 and 10 cm/s, a 1 cm x 1 cm magnet induces a 10 gm force in a 1mm induction member (Equation (1.1)), which is comparable with forces and torques produced by mini-motors. 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 loss-less 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 stroke based operation.

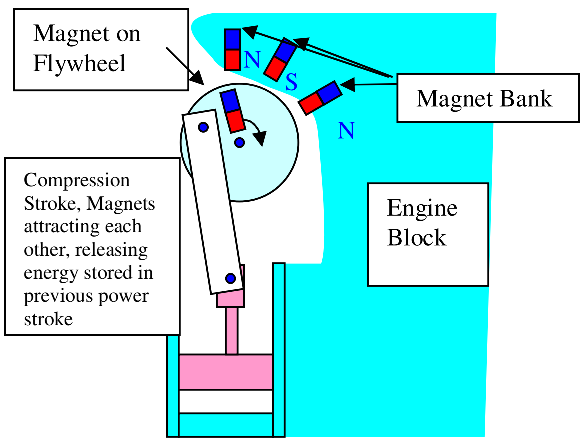


Figure 13: Engine (*simplified sketch*) with Flywheel and Block enhanced with Magnets, permitting storage of engine power magnetically.

One such mechanism converts the flywheel to a non-uniformly magnetically enhanced revolute pair. Figure 13 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].

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

where k_s is the maximum percent ripple in speed.

The enhanced flywheel system in Figure 13 uses high-power magnetics for 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 13 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.

The torque output of the engine is clearly the gas force as reflected through the slider-crank mechanism, plus any net torque produced by the magnet enhanced flywheel. Following Section 4, 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.

$$M=\frac{pA+m_{rec}g-m_{rec}w^2r(\cos(\theta)+\lambda\cos(2\theta))}{\cos(\phi)}r\sin(\theta+\phi)+\sum\tau_{mi} \quad (1.4)$$

where the first term

$$M=\frac{pA+m_{rec}g-m_{rec}w^2r(\cos(\theta)+\lambda\cos(2\theta))}{\cos(\phi)}r\sin(\theta+\phi)$$

is the torque of the engine without any magnetic enhancement (see [3]), and the second term is the total torque from all the magnets

$$M=\sum\tau_{mi}$$

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.

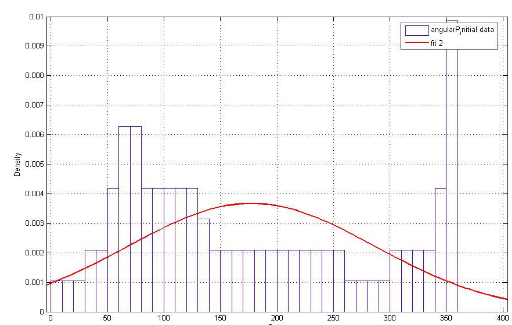


Figure 14 Magnetic Structure of engine block magnets used in conjunction with Enhanced Flywheel

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 engine block magnet is in an attracting position, pulling the rotor magnet 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.

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

Table 2 Engine Parameters

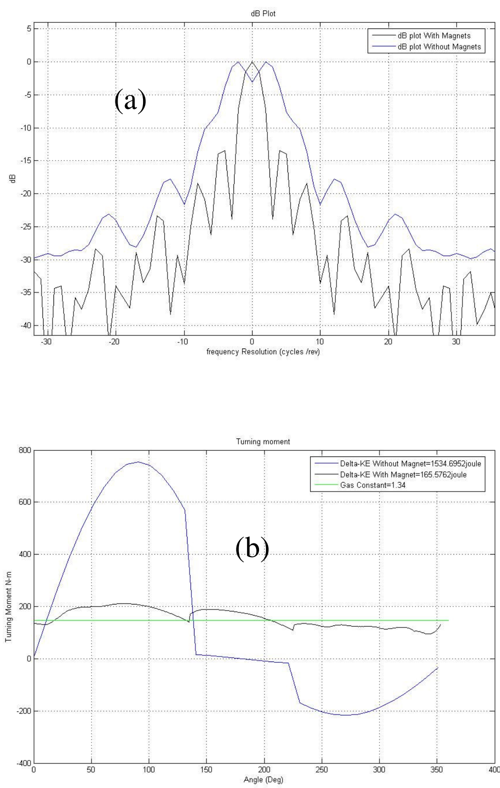


Figure 15: Harmonics (a) and Residual Ripple (b)

This procedure was adopted for the 2-stroke engine parameters shown in Table 2. The results are shown in Figure 15. Figure 15 (a) shows the spectrum of the torque, and Figure 15 (b) shows the torque as a function of phase of the stroke. Without the magnets, the delivered torque is highly variable – varying between 700 Nm max and -200 Nm min -, with an average of 150 Nm. The addition of the magnets to the flywheel creates a time-varying (but linear and lossless) load, which reduces torque ripple. Due to the periodic time-varying load, energy is transferred from harmonics 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 on the engine block, each about 3cm x 1cm) can fit within the space allocated for the flywheel system, and provide both inertia energy storage and magnetic energy storage. Since the magnet density is roughly the same as flywheel material (iron), magnetic storage is provided without reducing inertia storage. In addition, the magnetic storage can be finely customized as a function of angular position, unlike inertia storage. The resulting flywheel is lighter and has less torque ripple and vibrations.

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 residual, can of course be corrected with active control techniques, e.g. ISAD's. The passive harmonic reduction of course simplifies any required active control.

Clearly, we can equally well do the reverse of torque smoothing – by 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, by enhancing the pairs of the mechanism with customizable magnetic energy

8. Conclusions

We have presented 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. *As opposed to active control our methods embed intelligence in the geometry of the electromagnetic interactions.* 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. Our techniques can be used in conjunction with all currently known methods of mechanism dynamic control.

9. References

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