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Kinematic structure for robust mechanical architectures in robotic planetary exploration

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Kinematic Structure for Robust Mechanical Architectures in Robotic Planetary Exploration

John D. Hobbs [a], Joe Rooney [b]

[a] Astrium Ltd., Gunnels Wood Road, Stevenage, Hertfordshire, SG1 2AS , United Kingdom, E-mail: john_d_hobbs@compuserve.com

[b] Centre for Configurational Studies, Faculty of Technology, The Open University, Walton Hall, Milton Keynes, MK7 6AA, United Kingdom

Abstract

This paper describes new research into the kinematic structure of autonomous robotic systems, and into the associated design processes. The approach aims to develop novel insights and applicable tools and techniques for designing advanced mechanical architectures for planetary exploration systems. These should provide enhanced functionality for tackling complex autonomous operations, and improved levels of robustness in the face of the inevitable system faults.

Introduction

A major influence of recent trends in the design of space missions has been the proliferation of mission concepts that rely on advanced autonomy and distributed systems to achieve their objectives, and this is unlikely to change. By employing advanced autonomy techniques, the need for extensive and expensive ground support operations is reduced, and by employing distributed systems, the door is opened to achieving with a number of small, co-operating agents what was previously the domain of very large, and very expensive spacecraft.

As the objectives for such robotic missions – be they surface exploration, or free flying - become more complex, greater demands are placed upon the reliability and robustness to faults of the autonomous systems created for the task. In particular, it has previously been identified [Hobbs et al, 1996 [1]], that the design of the relevant mechanical architectures may be insufficiently flexible to meet mission goals. Future mechanical systems with the enhanced functionality necessary for tackling advanced autonomous operations, are even more likely to exhibit inadequate robustness in the face of the inevitable system faults.

New research into the kinematic structure of autonomous robotic systems offers the potential to develop fresh insights and new tools and techniques for designing mechanical architectures with improved robustness for future autonomous system development. The significance of this work, taken as an element of a new approach to the overall design process for autonomous systems is described.

A Morphology-Driven Robotics Design Process

The goal of this research is to establish a mathematically supported design process applicable to autonomous and robotic planetary exploration systems. The process sets out to capture the core mission objectives, characterise the type of system suitable for the defined mission, and then to assist in the identification of a suitable design solution. The major process steps are identified in Figure 1, and listed below:

- Define the system's target operational scenario
- Define the target mission
- Define system characteristics (goal) to operate successfully in the target scenario
- Search the design space of potential solutions for optimal / acceptable solutions
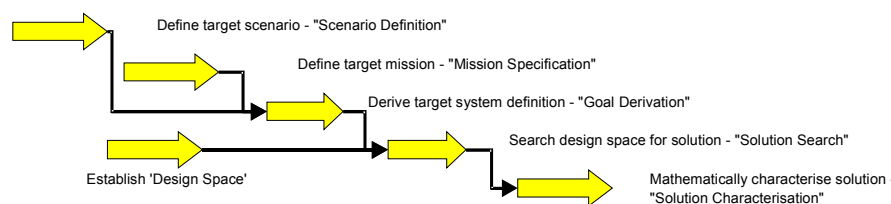- Evaluate and characterise the chosen solution

Figure 1: The System Level 'Morphology Driven Design' Process

Process Road Map

In order to be able to develop the 'Morphology Driven Design' Process, it is necessary to define / establish a number of distinct mathematical methods and tools which can be employed in order to achieve the overall design process. Some of these steps are able to utilise existing mathematical techniques, some require the derivation of new approaches. Figure 2 illustrates a development 'Road Map' of the work required:

Figure 2: Road Map for the System Level 'Morphology Driven Design' Process
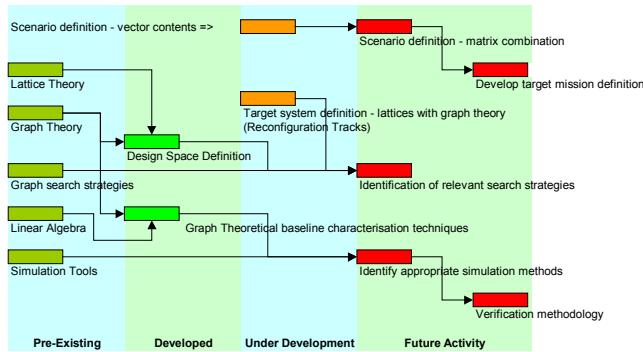
The following sections outline some of the more significant elements of this road map which have been developed, or which are in the course of development.

Kinematic Topology and Characterisation of Kinematic Systems

Kinematic topology is concerned with the organisational arrangement, juxtaposition and interconnection of components and sub-systems. Some relevant Graph Theory terms are defined below. A more comprehensive review is given in [Hobbs et al, 2000 [2]].

Kinematic Chains, Direct Graphs and Interchange Graphs: The fundamental step in applying graph theory to the kinematic chain of (eg) a locomotion subsystem is the generation of its interchange graph representation, where the links and joints of the chain are represented by vertices and edges respectively, [Rooney et al, 1983 [3]].

Kinematic Mobility: The concept of kinematic mobility, which represents the range of movement available to any specific kinematic system is of considerable interest in the analysis of planetary locomotion systems, ['Kinematic Design', 1995 [4]]. The mobility of a three-dimensional spatial, kinematic, system is given by:

$$M = 6(n-1) - 5j_r - 5j_p - 4j_c - 3j_s \qquad (1)$$

Where n is the total number of links, and j_r, j_p, j_c, and j_s are the total numbers of revolute, prismatic, cylindric and spherical joints, respectively.

Adjacency Matrices, Incidence Matrices and Characteristic Polynomials: The Adjacency Matrix (of (eg) an Interchange Graph) is defined as the n x n matrix whose ij-th term is the number of edges joining vertex i and vertex j, Wilson [5]. Similarly, the Incidence Matrix is defined as the n x m matrix whose ij-th term is 1 if vertex i is incident to edge j, and 0 otherwise.

[Yan et al, 1981 [5]] define the Characteristic Polynomial, P, of an Adjacency Matrix, A_m, as the determinant of the Characteristic Matrix, C, where $C = xI - A_m$, where x is a dummy variable, and I is a unit matrix of the same order as A_m.
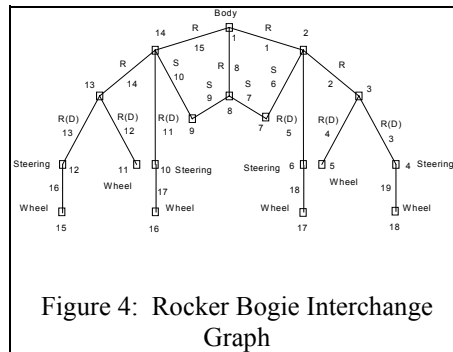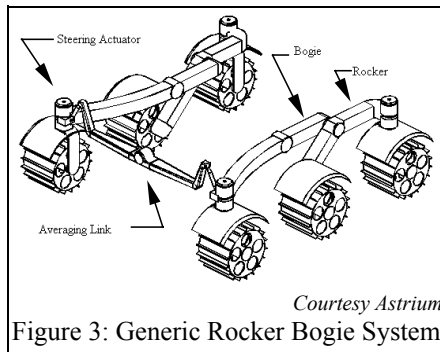
Degree Sequence: The degree sequence of a graph is the sequence generated by sequential enumeration of the degrees (ie number of connections) of the system vertices, [Wilson, 1996 [5]]. Conventionally one commences with the lowest degree, and works up.

Kinematic Geometry

Kinematic geometry is concerned with the type, range and complexity of the motion available to the components and sub-systems. The kinematic geometry of planetary exploration vehicles may be characterised using various Screw Theory techniques. These include Plücker Coordinates (specifically for location and motion of joint axes), and Mobility Analysis (specifically for the distribution of freedom and constraint in the motion of components and sub-systems). Further work will investigate how such characterisation may be used to define and determine those geometrical features which make for more successful systems and how specific kinematic geometry features can affect system robustness.

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Specific Results - Characterisation of a Typical Locomotion System

The techniques described can be illustrated by considering the example of a generic rocker bogie system – Figure 3. (Further results are given in [Hobbs et al, 2000 [2]]).

Figure 3: Generic Rocker Bogie System

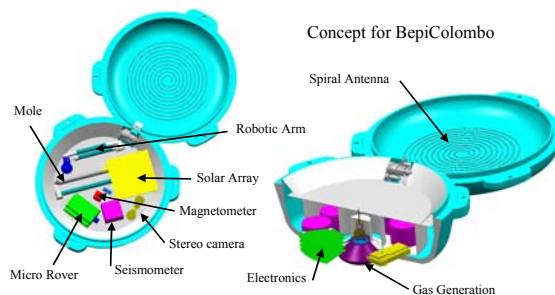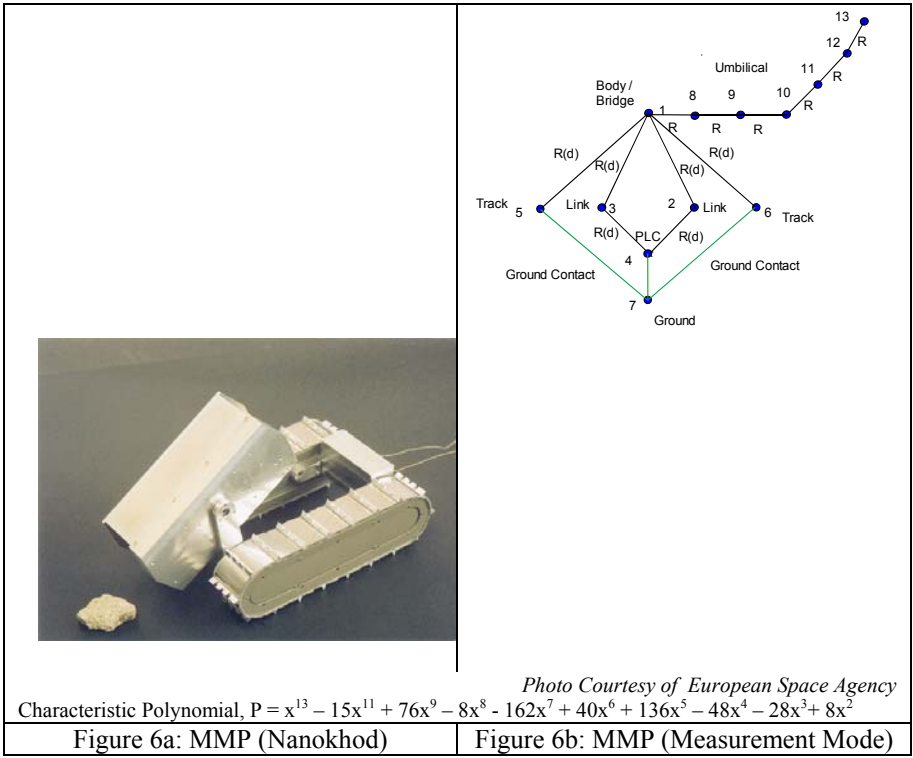Figure 4: Rocker Bogie Interchange Graph

The degree sequence for the Rocker-Bogie system can be shown to be (1,1,1,1,1,1,2,2,2,2,2,2,3,3,3,3,4,4), and by applying Equation 1, the mobility is found to be 15. The Characteristic Polynomial, evaluated using Maple, is:

$$P = x^{18} - 19x^{16} + 137x^{14} - 489x^{12} + 943x^{10} - 1003x^8 + 577x^6 - 171x^4 + 23x^2 - 1$$

Autonomy of a Mercury Lander

We consider the various options for the surface element (lander) of ESA's planned 2009 BepiColombo mission to Mercury (Figure 5). Surface Mobility of the lander is achieved through a number of separate robotic elements - the Mole Deployment Device (MDD), the Mercury Mobile Platform (MMP), based on Nanokhod - Fig 6(a), the Panoramic Camera System (CLAM-S), and the Robotic Arm (ARM). The techniques discussed earlier can be used to characterise the various mobility elements of the system. Figure 6(b) illustrates the MMP represented in graph theoretical format.

Figure 5: One Configuration of the BepiColombo Mercury Surface Element

Photo Courtesy of European Space Agency

Characteristic Polynomial, $P = x^{13} - 15x^{11} + 76x^9 - 8x^8 - 162x^7 + 40x^6 + 136x^5 - 48x^4 - 28x^3 + 8x^2$

| Figure 6a: MMP (Nanokhod) | Figure 6b: MMP (Measurement Mode) |

Characterisation of Operational Modes

Table 1 identifies a number of nominal operational configurations / modes. Additional to these, further fault (and failure) conditions can be identified. All of these can be characterised in a similar way, and the transition between them can be considered to form a set of 'reconfiguration trajectories', that is, a set of mathematical definitions sequenced to represent the evolution of system configuration as it moves through its various operational states / modes

The graph theoretical representation of one of the nominal modes is presented as Figure 7 for illustration purposes. The resulting polynomial coefficients for several of the nominal modes are plotted in Figure 8.
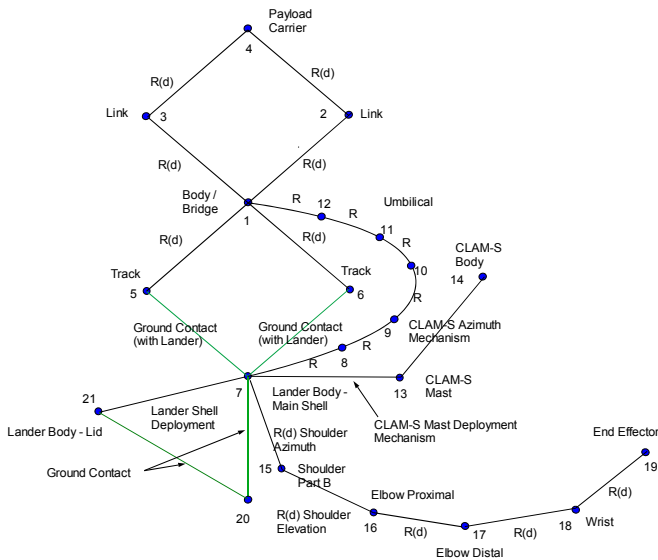

Figure 7: Mode 2 - Lander Deployed, MMP and Mole On-Board

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{A,B,C,D}(No Items Deployed)

{A,B,C}   {B,C,D}

                        {B,C}

          {A,B,D}   {A,C,D}
                                        {B,D}

{A,B}   {A,C}   {C,D}

          {B}   {C}

                    {A,D}

{A}   {D}

                {}(All Items Deployed)
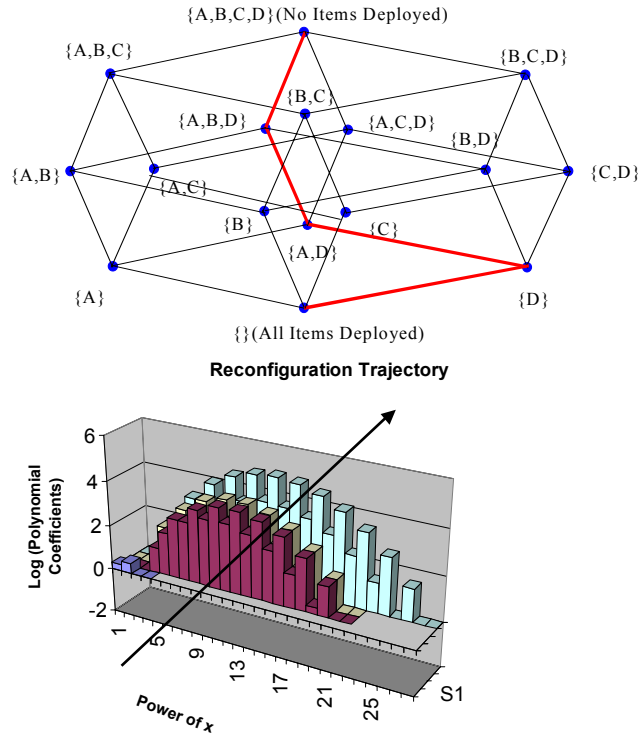
Reconfiguration Trajectory

Figure 8: Variation in Reconfiguration Trajectory Polynomial Coefficients

As an alternative to the representation by polynomial coefficients alone, the available permutations for the system configuration, whether nominal modes or fault modes, can be represented by the vertices on a hierarchical lattice (hypercube). This approach is illustrated in Figure 9, which also defines the various vertices in terms of lander equipment disposition.

Vertex	Description	Vertex	Description
A,B,C,D	Lander not deployed	B,C	MDD & ARM deployed
A,B,C	ARM only deployed	B,D	MDD & CLAM-S deployed
A,B,D	CLAM-S only deployed	C,D	MDD & MMP deployed
A,C,D	MMP only deployed	A	MMP, CLAM-S & ARM deployed
B,C,D	MDD only deployed	B	MDD, CLAM-S & ARM deployed
A,B	CLAM-S & ARM deployed	C	MDD, MMP & ARM deployed
A,C	MMP & ARM deployed	D	MDD, MMP, & CLAM-S deployed
A,D	MMP & CLAM-S deployed	{}	Lander fully deployed
Figure 9: BepiColombo Surface Mobility as a Hypercube Lattice			

We can take any route through the lattice vertices as a 'reconfiguration trajectory'. In the case of the fundamental operational modes we can identify this trajectory within the lattice as shown in Table 1, and highlighted in red in Figure 9.

MODE No.	DESCRIPTION	VERTEX
1	MSE on surface, no elements deployed	{A,B,C,D}
2	MSE on surface, CLAM-S deployed	{A,B,D}
3	MSE on surface, MMP on surface, MDD on board	{A,D}
4	MSE on surface, MMP and MDD on surface	{D}
5	MSE on surface, MMP measuring, MMD on surface	{D} special
6	MSE surface, MMP & arm interacting, MMD on surface	{}
7	MSE surface, MMP on surface, MMD & arm interacting	{} special

Table 1: Fundamental Operational Modes as Reconfiguration Trajectory

NOTE: Those items identified 'special' represent alternative subsets of the nominal mode, for which separate 'reconfiguration trajectories' could be defined.

Concluding Remarks

We have demonstrated that potential exists for the application of novel design approaches based on the application of tools and techniques from kinematic theory in order to derive systems which are more robust against failure. It is considered that it is feasible to establish schemes whereby locomotion systems can be analysed and classified, and the results presented graphically. The methods proposed are shown to fit clearly into an overall design process, and practical means whereby the implications of this work could be incorporated into real designs have been discussed.

Acknowledgements

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