__Near Minimum Time Geometric Paths for Robot Manipulators__, IEEE Trans., on Auto. Cont., Vol. AC-31, Vol. 6, June 1986.

*[26] Shin K.G. & McKay N.D. (1986), __A Dynamic Programming Approach to Trajectory Planning of Robot Manipulation__, IEEE*Trans,. on Auto. Cont., Vol. AC-31, No. 6, June 1986.*

[27] Bukov P.V & Zubov N.E (1986), __Relay Control Using an Algorithm in the Predictive Control Model__, IEEE Trans. of Robotics & Automation, Vol. 47, Part I, No. 6, pp. 762-767.

References

[1] Dixon J.R (1991), **Engineering design Science**, Application of Design Science, Mechanical Engineering, IMechE, U.K Feb 1991.

[2] Hubka, V & Ernst Eder, W(1988), **Theory of Technical Systems**, Springer Verlag.

[3] Hubka, V (1989), **A Curriculum Model**, Applying the Theory of Technical Systems, Int. Journal Engng Educ, Vol. 4, No.3, pp. 185-192.

[4] Hilton D.J (1988), **Contermporary Science and Natural Explanation**, The Harvester Press Limmited, U.K.

[5] Ernest Eder W(1991), **Education for Engineering Design**, The State of Education, Int. Journal of Engng Education, Vol.4, No.3, pp. 167-184.

[6] Westerburge A.W, Stephaopoulas G & Shah J. (1974), **The Synthesis Problem with Some Thoughts on Evolutionary Synthesis in the Design of Engineering Systems**, Proc. of Symp. on Basic Questions of Design Theory, Colombia University, Elsevier Pub. Co. Inc.

[7] French M.J (1971), **Conceptual Design for Engineers**, Springer Verlag.

[8] Chen P.P (1984), **Entity Relationship Approach to System Analysis and Design**, John Wiley & Sons Co.

[9] Bradley D.A, Dawson D, Burd N.C & Loader A.J (1991), **Mechatronics**, Chapman & Hall Ltd.

[10] Wiener N. (1961), **Cybernetics**, MIT Press, Cambridge, U.S.A.

[11 Baily R.L (1978), **Discipline Creativity for Engineers**, Ann Arbor Science Publishing Inc

[12] Bohm W. (1975), **Causality and Chance in Modern Physics**, Routledge and Kegan Paul, London.

[13] Sharpe J.E.E (1978), **Application of Bond Graphs to the Synthesis and Analysis of Telechir and Robots**, 3rd Int. CISM-IFT oMM Conference on Theory and Practice of Robots and Manipulators, Sept. 1978, Udine, Italy.

[14] Sharpe I.E.E & Siva K.V (1986), **Bond Graph Synthesis and Analysis of Covarient Bilateral Servo Systems in Manipulator Control Systems**, Proc. of 11th IMACS, Oslo, 1987.

[15] Sharpe J.E.E & Siva K.V (1987), **Covarient Control of Bilateral Servo for In - Orbit Manipulators**, Proc. 1st European In - orbit Operations technology symposium, Dramstadt, Germany.

[16] Beaman J.J & rosenberg R.C(1988), **Constitutive and Modulation Sturcture in Bond Graph Modelling**, Trans. ASME, J. of Dyn.Sys. Measurement and Control, Vol. 110, pp. 392-402, Dec. 1988.

[17] Karnopp D.C (1974), **Synthetic Dynamics : Bond Graphs in Design**, Proc. of Symp. on Basic Questions of Design Theory, Colombia University, U.S.A.

[18] Mesarovic M.D. & Echman D.P (1961), **On Some Basic Concepts of General Systems Theory**, Proc. of 3rd Int. Congress on Cybernetics. Hammer, Belgium 1961.

[19] Paynter H.M (1961), **Analysis and Design of Engineering Systems**, MIT Press Cambridge, U.S.A

[20] Medland A.J (1989), **The Appllication of Constraint Modelling Technique to the Description of the Design Process**, Int. Conf. on Engng. Design, Harrogate, C377, 1989.

[21] Hood S.J & Palmer E.R (1987), **The Design Analysis for Reliability Tool**, IBM Corporation, Research Div., Yorktown Heights, N.Y. 88(TP10-4:00)

[22] Luh J.Y.S (1983), **An Anatomy of Industrial Robots and Their Control**, IEEE Trans. On Automatic Control, Vol. AC - 28, No.2, PP. 133-153, Feb 1983.

[23] Takano M (1987), **Speed Up of Robot Motion**, Bull. of Japan Soc. of prec. Engng., Vol. 21, No. 2, pp. 91-94, June 1987.

[24] Shinners S.M (1978), **Modern Control Theory and Application**, Addision - Wesley Publication Co.

[25] Shin K.G. & McKay N.D. (1986), **Selection of**

Application of the model presented in Fig 7, in this energy domain results in an equivalent model which requires very detailed expansion (Fig.14-a). The level of reticulation as stated previously is decided upon by the designer based on the derived criterion function. What is important is that the concept of causal synthesis, as well as providing an analytical structure for synthesis does allow the reticulation to take place at a very detailed level too, (Fig.14-b the reticulated bond graph, and (c) the simulation results).

Conclusion

It has been argued that the newly forming concept of Design Science requires an "analytical" general approach for it to leave the sphere of conceptuality and thus render conventional overgeneralizations, ineffective. For this the process of synthesis was identified as the heart of the design process and the only segment which consistantly defies any structural impositions. It has, however, been shown that a systematic approach could cater for peculiar charateristics of this segment of design process. This was shown to be achieved through causal structuring of the synthesis. To this effect an Ideal Conceptual Design in a nondisciplinary environment, could be synthesized. The proposed ICD, was then adopted as the criterion design with the highest degree of integrity allocated to technical optimality. The proposed synthesis was evaluated outside the framework of any energy domain and was then allowed to manifest itself within the bounds of individual disciplines through physical embodiment. The latter took place in two distinct disciplines of electric machines and hydrostatics. In both fields, the ICD underwent a systematic morphological change while sustaining topological characteristics. Whence it was shown that the outcome of the synthesis was valid and the causal approach to synthesis was justified even when none of the conventional disciplinary governing laws were present.

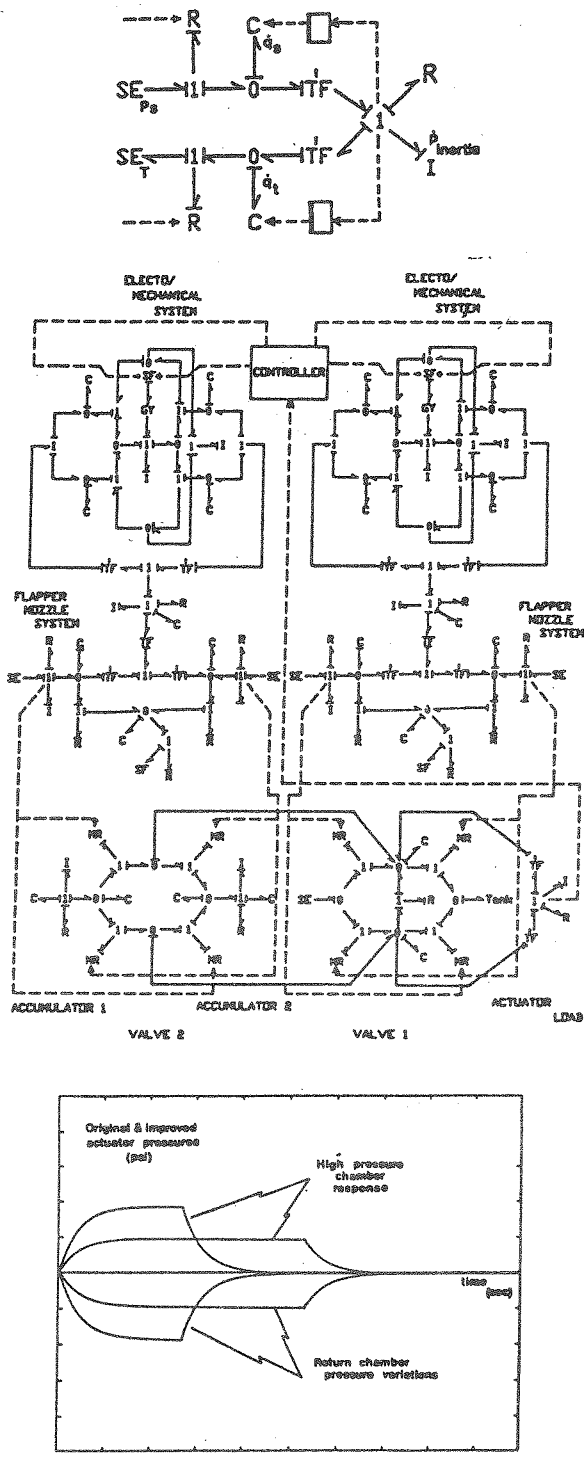


Fig.14-(a) Represents the hydostatic equivalent of the ICD indicating the supply and tank channels. (b) bond graph for two, two stage electrohydraulic pilot operated valves connected through in parallel to the actuator chambers & (c) the simulation results.

velocity trajectory would thus be described as :

$$dx/dt = Gt^3 (t-T)^3$$

where G = Constant and the acceleration trajectory is given by :

$$d^2x/dt^2 = 3Gt^2 (t-T)^3 + 3Gt^3 (t-T)^2$$

which is a Particular form of :

$$\frac{d^2x}{dt^2} = k_1 t^m (k_2t - \beta)^n (k_3t - a)^l$$

and the final jerk trajectory would be given by :

$$J_{max} = [(-840 S/T^7) t(t-T)(5T-5tT+T^2]$$

The Inverse Dynamic Feedforward algorithm for the predictive control strategy [27], for compensation towards any deviation from the prescribed trajectories, is adopted as the performance index.

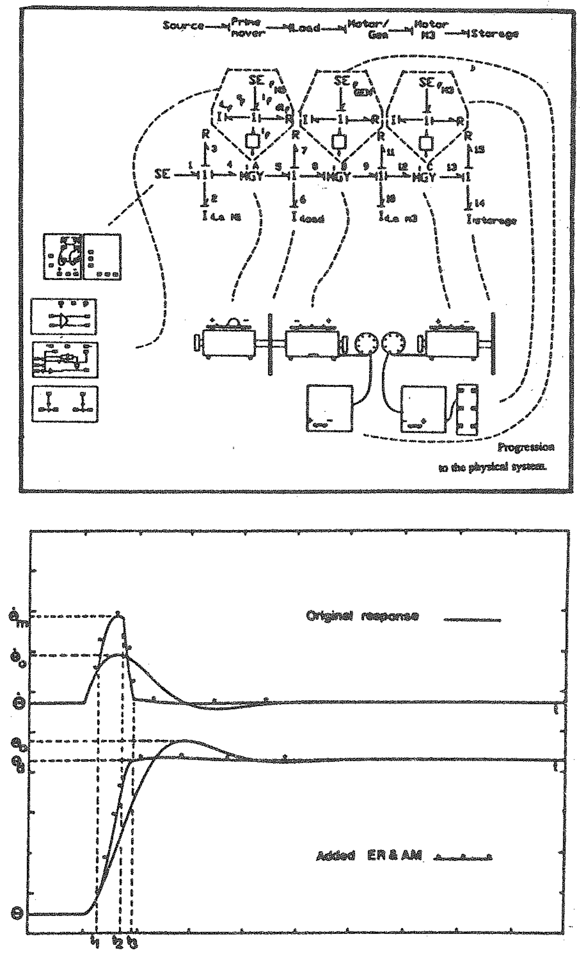
2 - Physical Embodiment, Electric Machines

Physical embodiment, as described earlier forms the content of the second stage in the synthesis of the ideal conceptual design.

The emphasis is on the systematic progression of a design from a conceptual model to its physical embodiment. That is to qualify the validity of such a conceptual approach by showing that it can predict the consequence of disciplinary embodiments, thus justifying energy domain independency during causal synthesis. Within the bounds of individual disciplines, however, the reticulation and the level of complexity is decided by the designer. Whence to leave the sphere of conceptuality, the proposed ICD is evaluated within the framework of relevant energy domains. Here, the criterion design is introduced to the domain of DC machines since a great majority of robotic manipulators utilize electric and in particular electric DC machines as means of actuation. The introduction as suggested by Fig.6, is followed by interdisciplinary expansions through substitution of physical elements for the multiports, thus moving the proposed synthesis towards physical realisation Fig.13, where the simulation results are also added.

3 - Physical Embodiment, Hyrostatic Domain

A further introduction of the ICD in an appropriate discipline takes place within the bounds of hydrostatic energy domain.



Where,

t_1= Activation of (M3) and (GEN) field windings.
t_2= Reversing the polarity on (M3) field windings.
t_3= Disengaging (Gen) and (M3) through inactivation of corresponding fields.
θ= Position.
θ= Angular velocity.
θ_d= Desired position.
θ_o= Original position overshoot.
θ_o= Original maximum velocity obtained.
θ_m= Maximum velocity from addition of ER & AM.

Fig.13- Substitution of dc machines as motors (M1, M2 & M3) and generator (GEN), for the elements of the reticulated ICD within the field of electric machines and the corresponding simulation results.

time and energy dissapation. Here the system responce is heavily influenced by the initial conditions. Analogue computational model for the Bang-Bang controller and the corresponding phase Plane is presented in Fig.11. The proposed switching algorithm, however, does entail important implications regarding the system Jerk characteristics. This problem is Particulary associated with high speed motion [25,26]. Consequently, the velocity profile has to utilize all the available energy. The important constraint for such trajectory would be that of the maximum allowable Jerk.

The boundary conditions could thus be stated as:

at $t=to$ $x=0$, $dx/dt=0$, $d^2x/dt^2=0$ & $d^3x/dt^3=0$

and at $t = T$

$x=S$, $dx/dt=0$, $d^2x/dt^2=0$ & $d^3x/dt^3=0$

where $S=$ desired position, and $T=$ final time.

The implication of such boundary condition is that the rate of change of acceleration has to have a unique tangential trajectory, parallel and along the time axis in a velocity-time plane. Here a minimum - time, maximum jerk, two stage strategy indicates a perfect bell, polynomial function for the velocity profile. This algorithm will be called a Maximum Jerk Bang - Bang Parabolic Blends or MJ(BBPB) (Fig.12). The

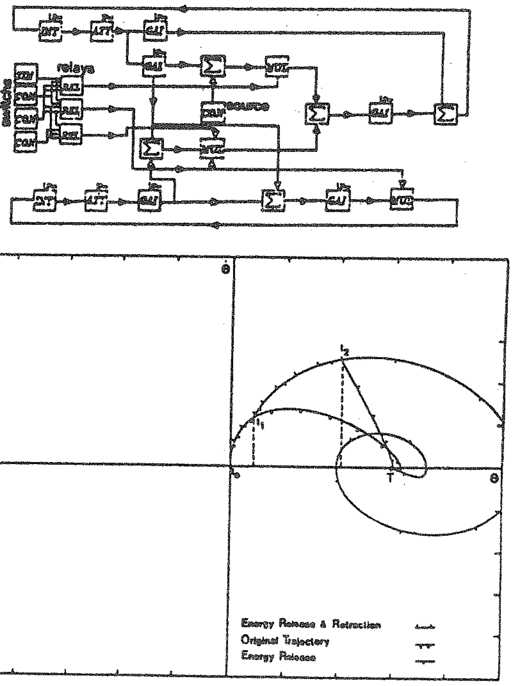


Fig.11- Analogue computational model for the Bang - Bang controller and the corresponding phase plane trajectory

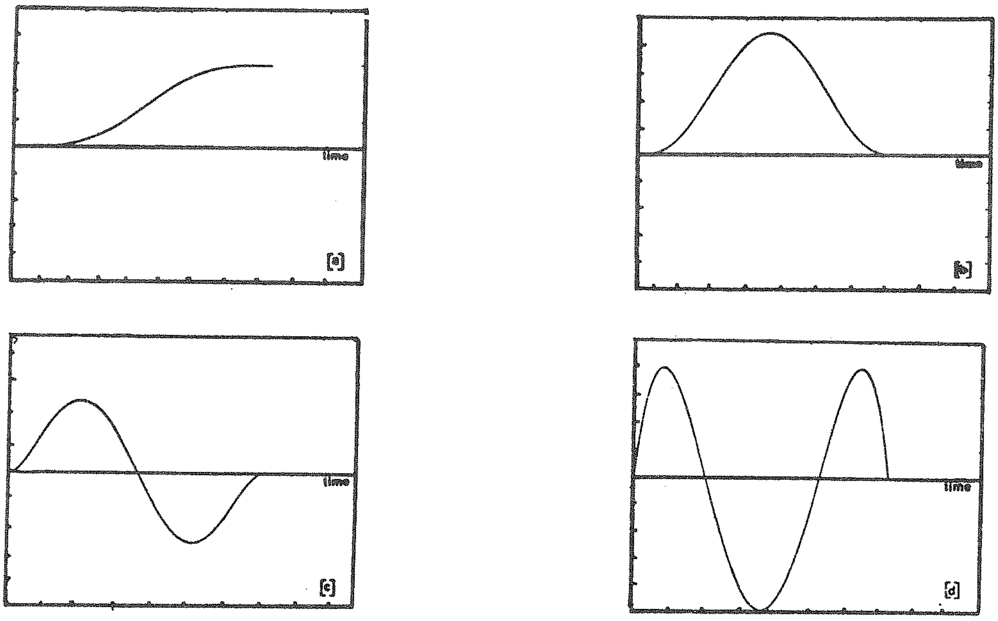


Fig.12- Maximum Jerk Ban - Bang Parabolic Blend Trajectory Planning MJ(BBPB) Strategy, a - Position trajectory, b-Velocity profile, c-Acceleration profile & d- Jerk profile

of energy to increase acceleration. The additional energy could be fed into the system after the original energy source has overcome the resting inertia, or it can be used at the same time with the original source to result in a higher initial acceleration. The latter possibility points at very high rates of change of acceleration or Jerk which will have to be included in the boundary condition.

If the extensions are to take place through a series configuration what, in effect, is being fed into the system is the effort, whereas in parallel configuration it would be the flow that is being increased. One question is that which one of the two would be more efficient in obtaining higher operational velocities by the inertia? Furthermore, following the suggested minimalistic approach to the synthesis, which one of the two routes require minimum functional connectivity?

The causal structure of the energy gates down stream of the modulatory gyrator (Fig.9) is also revealing. The preferential causality assigned to either form of the energy conserving one - ports, indicate an integration with respect to time of either flow or effort entering them. The implication is that the discharge might not necessarily be continuous and in effect, follows a decaying pattern which for a linearly operating element can be a ramp output. Hence the choice of elemental parameters has to be such that the rate of charging complements retardation of the inertia during braking. Alternatively the controller algorithm should be capable of compensating for any deviations from this requirement. If so, a high power consumption by the controller can have an adverse effect on the validity of the adopted approach to the solution. Here the charging and discharging can take place through a switching procedure which will affect the controlling strategy. If a switching procedure is to be included in the controller strategy, a decision would have to be made on the criteria for switching (i.e. time-activation, position - activation or error activation criterion?). The bond graphs shown in Fig.10 (a &b) indicate the alternative structures analyzed in Fig.9. The inclusion of energy storage elements and bidirectional power bond, unconventional as they are, and the multi - facet operation of the system are also shown in Fig.10.

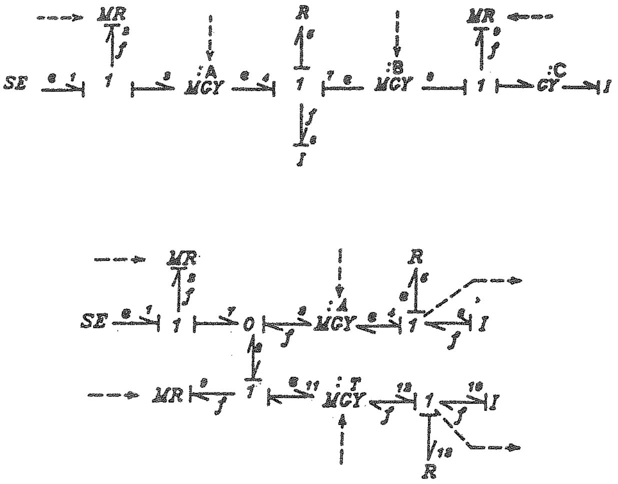


Fig.10- Structure of alternative ICDs

1-3- Maximum Jerk Switching Criterion

The conventional analysis techniques could be adopted to analyse various features of the proposed designs. As an example, the controlability and observability of the system can be studied. Here the non - singularity of matrix [B AB], (where $dx/dt= Ax + Bu$) ensures controlability and furthermore, the non - zero solution of the matrix $[L^T A^T L^T]$ (the output state space equation) is a measure of observability of the synthesized systems.

The preferential causality associated with the inertial element in Fig.9, indicates the existence of a common flow junction upstream of the gyrator. The summation of efforts into this ideal three port, points at the possibility of causal conflict. A controlling mechanism would therefore have to be implemented.

The application of optimal control theory to the Space Vehicle Trajectory Planning [24], dictates the adoption of a Bang - Bang control strategy as an optimal solution with optimized

1-2- Regenerative Braking

It is apparent that to increase the energy flow to the system, a secondary power source would have to be introduced. Any such introduction has to take place through the existing energy gates (i.e. the three port junction structures in Fig.9). Here the concept of causal feedback in recursive synthesizing reticulation becomes increasingly useful. The choice between the two energy gates depends upon whether the additional energy flow should be fed into the system down - stream or up - stream of the gyrator GY: A. Inclusion of a secondary source would, however, prove impractical. The proposed solution is to design an energy Release & Absorbtion Mechanism (ER&AM). In other words, application of the concept of Regenerative Braking so that instead of applying energy to retard the moving arm, the existing kinetic energy of the arm could be retracted, stored and reused as a booster source

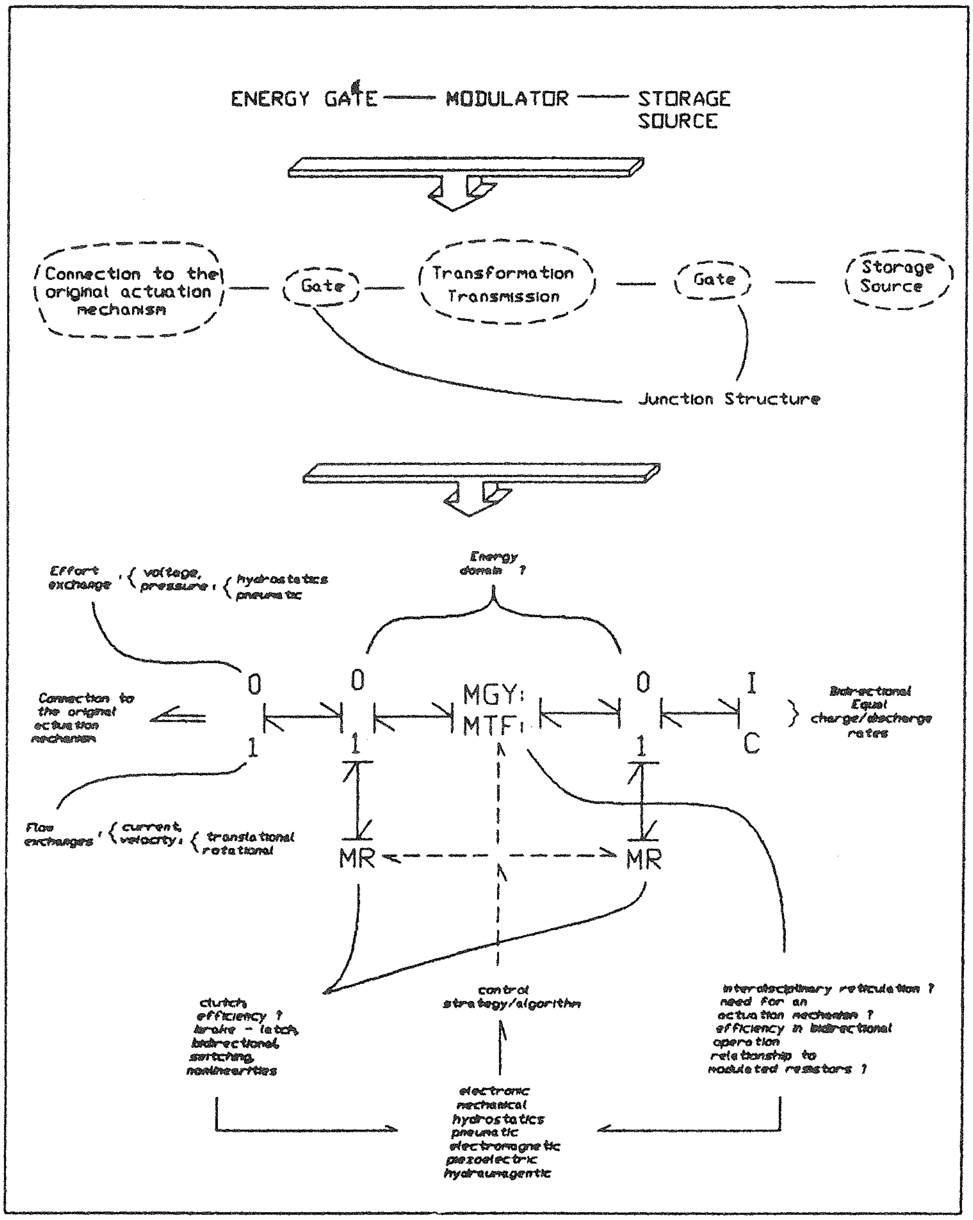


Fig.9- Energy domain complexities indicated by causal feed back at the early stages of synthesis

although the result of synthesis is a conceptual model, a variety of conventional analysis techniques can be implemented to analyse it and conventional or devised control strategies could also be included.

2 - Physical Embodiment which takes place within the bounds of Electric Machines and Hydrostatic domain.

1-1- Problem Formulation

There is an incentive in competitive environments for robot suppliers and potential users alike to select the fastest robot from a range of otherwise similar machines. Improving the speed of robotic manipulators has been the subject of numerous research programmes [22]. It, however, is apparent that the decisive factor is the amount of power available to perform a task [23] and this is dependent, to a great extent, on the energetic structure of any proposed design. Thus the problem statement can be outlined as "Existing Robotic Manipulators Must Operate Faster". It should be noted that the approach to the choice of an example is primarily dictated by the conceptual definition of mechatronics.

The criterion design at its elementary stage, contains a series of monodic or diadic functions representing the root relationships between the Energy Source (So), the Transformation / Transmission Module (TM) and the Energy Sink (Si) as shown below, followed by the governing description of the (TM) : $e_o\, f_o = \varepsilon\, e_i\, f_i$
Where ε is the transmission coefficient. The maximum power into (TM) is limited by the characteristics of (So). The system power consumption, on the other hand, is primarily dependant upon (Si), assuming an optimum dissipation within the structure of (TM). Any diviations from zero dissipation and inclusion of controlling constituents would result in the expansion of the proposed criterion design in a manner shown in Fig 7:

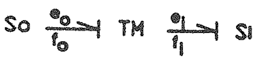


Fig.7- Augmented Bond Graph

Expansion of an elementary Bond Graph follows the "Recursive Reticulation Process". This is recursive because the same pattern may be applied locally all over the design process. The depth of recursion is inversely proportional to the extent of conceptualization until the objective function has been satisfied. The combination of parameters associated with elements R_2, GY and R_5 can cater for a range of possible constraints which may be associated with the controller, actuator and the inertia. The system could thus be represented as shown below, where a basic position - velocity feedback is also included in the block diagram. (Fig.8), is the phase trajectory for the model indicating proportional parameter alterations.

$$\frac{P6}{I_6} \rightarrow \frac{P6}{I_6}\max \Rightarrow \frac{P6}{I_6} = \frac{AE_1}{A^2 + (R_2R_5)}$$

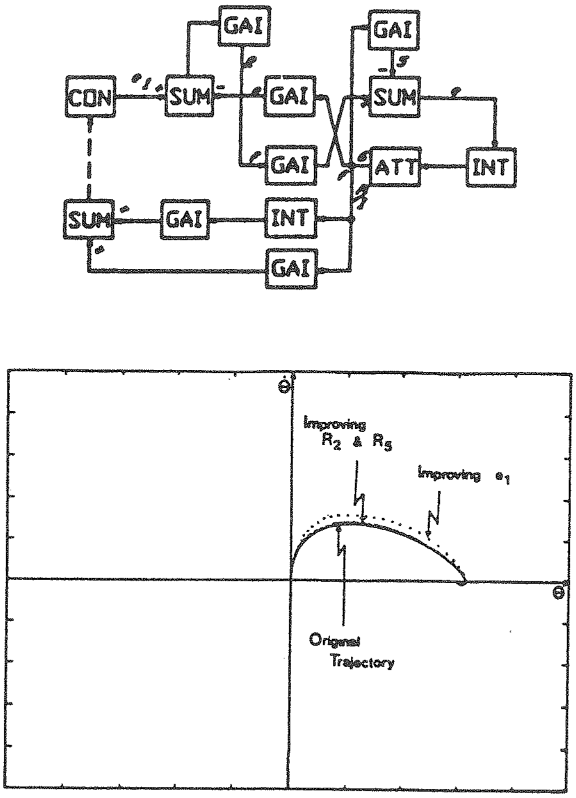


Fig.8- Block diagram and the corresponding phase Plance

minimisation, on the other hand, would manifest itself in the necessity for minimum functional connectivity. Thus all nonessential initial constraints imposed by the problem definition should be retracted at the elementary stage of the design process. In mechatronic design the informational point of view could provide strategic quidance. It is instrumental to realise that when the subsystems are fully interactable, high orders of the output can often be ignored; it is the orderd of the input that causes chaos in the creative thought process. A complete picture of the approach outlined above, is presented in Fig.6.

The approach has two crucial facets, a) causal structuring, and b) minimum synthesis. The approach would therefore permit and encourage all form of analysis by being: a) open to conventional analysis techniques, b) in a position to readily place mathematical, topological and other descriptions of the system at the designer's disposal, and c) complementary and in complete harmony with computerised tools such as CAD/CAM analysis for manufacturability, quality control or reliability [21].

Study of failure modes, for example, as part of reliability factor, bare further testimony to the appeal and effectiveness of causal structuring during synthesis. Here operational seizures due to underdesigning and functional seizures due to causal discontinuities are amongst evaluation points which could be readily analysed.

Implementation in Mechatronics

Here the implementation of causal structuring and its robostness in conjunction with technical precession in mechatronic synthesis of multidisciplinary systems can be illustrated.

The implementation takes place in two stages of:

1 - Formulation of the ICD. Causal structuring is implemented in synthesis of the ICD and the conceptual model is constructed independent of any energy domains. It is also shown that

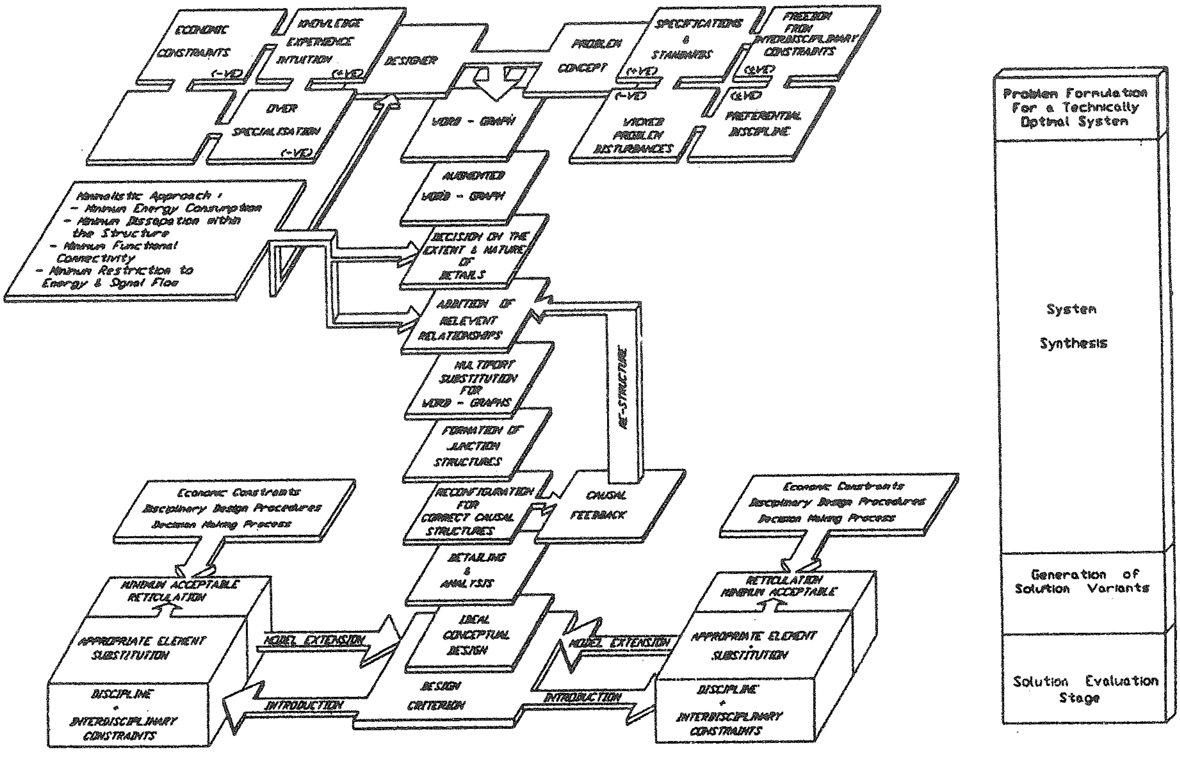


Fig.6- Causal synthesis in nondisciplinary design methodology

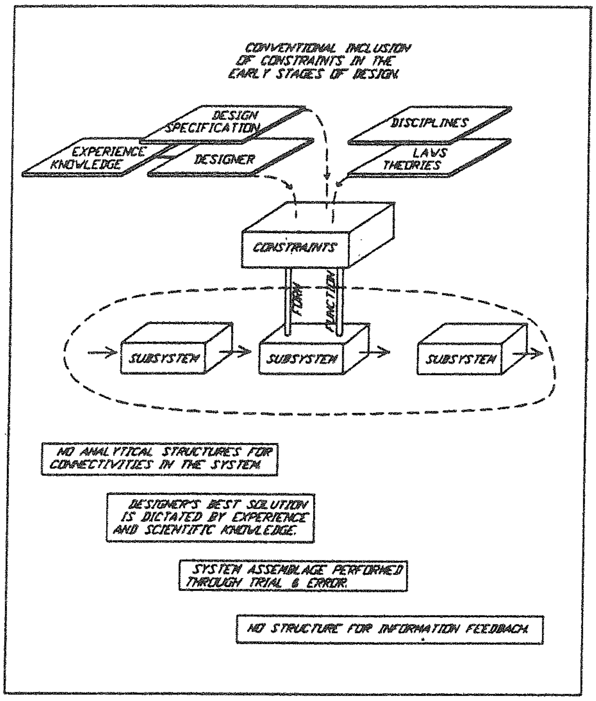


Fig.3- Conventional inclusion of constraints in the early stages of design

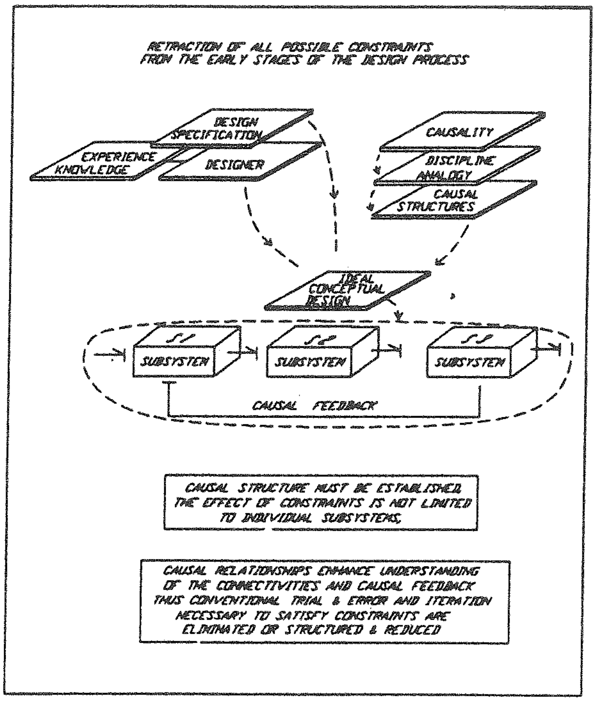


Fig.4- Retraction of all possible constraints from the early stages of the design

enegetic systems as a prerequisite to the problem statement of a specific design. The nature of a mechatronic criterion function is therefore based on flow of energy, materials and information, which means the adherence of proposed models to the concept of continuity of energy. The continuity of energy requires the generalised criterion to address the energy balance and the energetic efficiency in a system. The characteristics of any deviation from optimum energetic efficiency, is primarily dictated by the system impedance. This forms a particular aspect of the set of fundamental constraints necessary in the absence of disciplinary design structures. For this, the concept of system impedance may be decomposed into two subspaces within the energetic sphere in the shape of resistive and inertial constituents. Minimisation of the impedance could be primarily associated with the energy dissipation elements within the concept of energy continuity, assuming that the total inertial components is minimum (Fig.5). Inertial

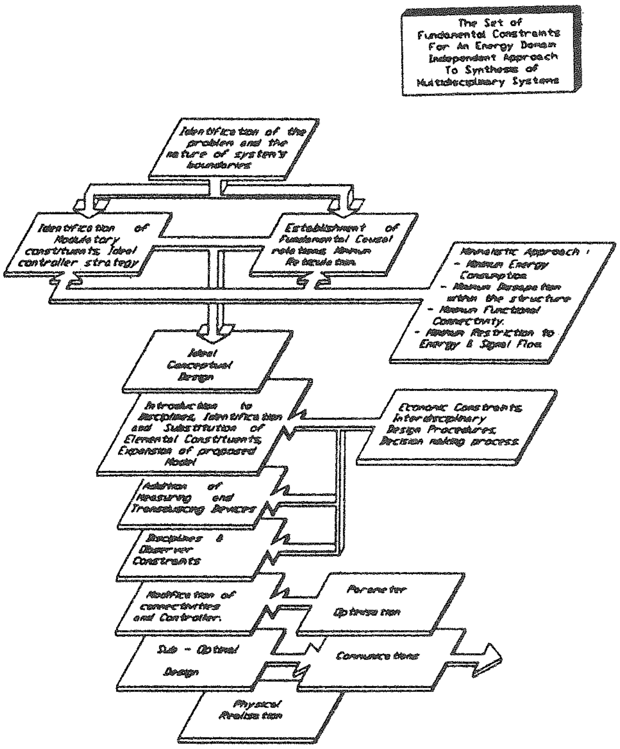


Fig.5- Minimalistic set of constraints in energy domain independent approach to synthesis

sphere of conceptuality [6,7] and move towards a physically realisable system. This takes place through appropriate substitution of existing disciplinary mechanisms for the multiports of the ICD. The product of this insertion is a system with similar fundamental behaviour to that of the ICD. But unlike the idealised multiports, the interdisciplinary modules will possess practical characteristics which may be far from ideal. The resulting physically realisable model may thus exhibit lower efficiencies and increased nonlinearities. But the nature of existing design environments may dictate constraints [20] and proiorities such as form, content, dimensions, prices, manufacturability, etc...., different from that of technical optimality (Figs 3 & 4). The question then turns to a point of reference for comparison so that the range of solution variants can be narrowed by the process of elimination. Hence, the proposition is to adopt the optimized ICD as the criterion function.

Criterion Function

A synthesized ICD has a topological **structure** and any parameter alterations may be evaluated through state apace analysis of the model. Since the state matrices have been deduced from the causal structures, the effect of any changes on the entire bahavioural pattern of the system can be readily observed. In a non - causal system formulation, recognition of those elements which might be most directly affected down stream of any parameter changes is much more difficult. This is particularly so when the systems are described and modeled by high order differential equations. Futhermore, computer compatibility of the approach eliminates the necessity for direct equation formulations.

Formulation of an ideal conceptual design, by following a generalized non - disciplinary approach, requires the reticulation process to aim at fulfilling an objective function; an imposition based on more fundamental aspects of

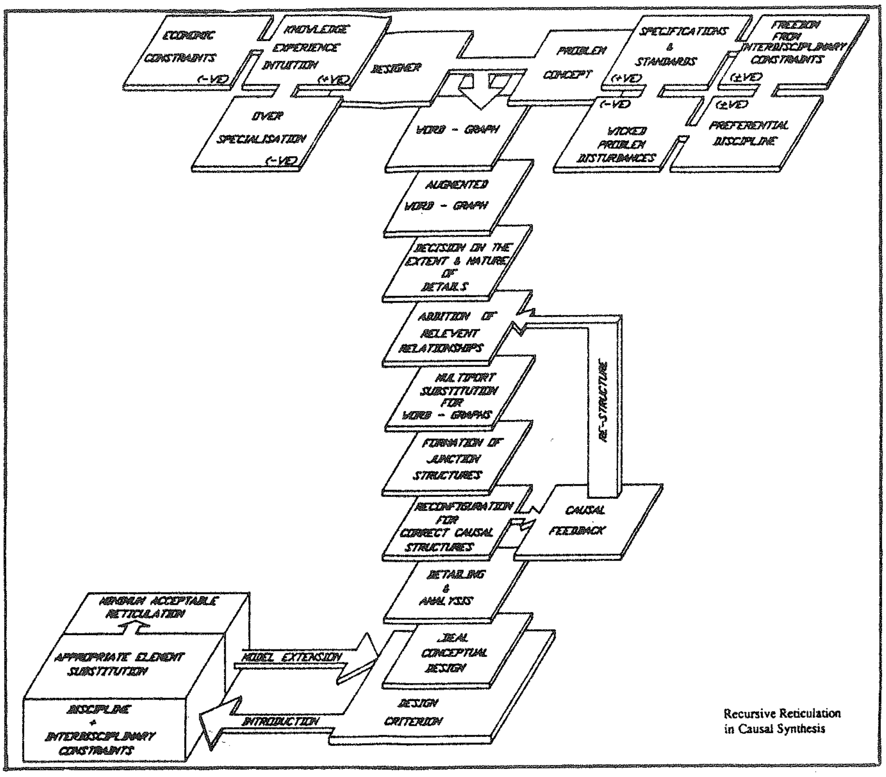
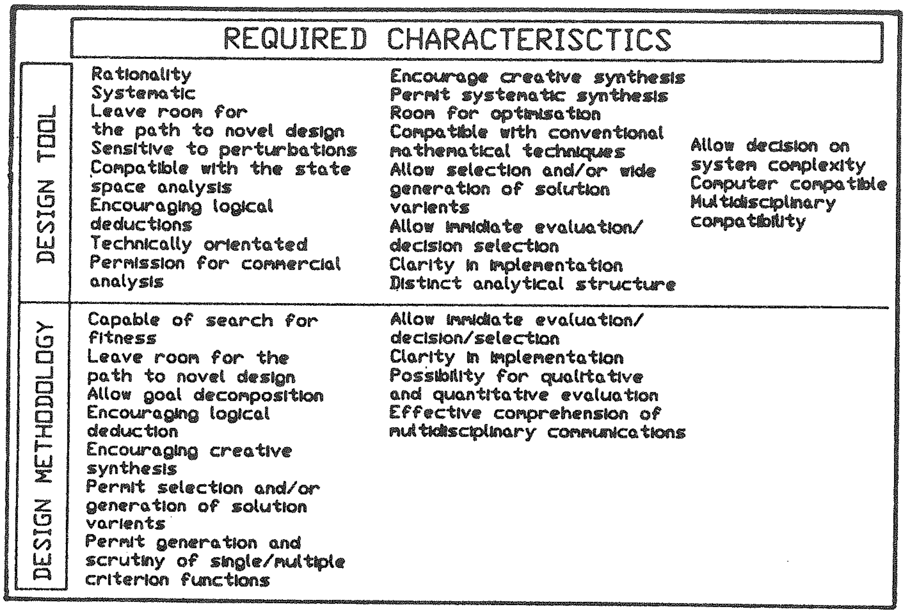


Fig.2- Recursive reticulation in causal synthesis



	REQUIRED CHARACTERISCTICS		
DESIGN TOOL	Rationality Systematic Leave room for the path to novel design Sensitive to perturbations Compatible with the state space analysis Encouraging logical deductions Technically orientated Permission for commercial analysis	Encourage creative synthesis Permit systematic synthesis Room for optimisation Compatible with conventional mathematical techniques Allow selection and/or wide generation of solution varients Allow immidiate evaluation/ decision selection Clarity in implementation Distinct analytical structure	Allow decision on system complexity Computer compatible Multidisciplinary compatibility
DESIGN METHODOLOGY	Capable of search for fitness Leave room for the path to novel design Allow goal decomposition Encouraging logical deduction Encouraging creative synthesis Permit selection and/or generation of solution varients Permit generation and scrutiny of single/multiple criterion functions	Allow immidiate evaluation/ decision/selection Clarity in implementation Possibility for qualitative and quantitative evaluation Effective comprehension of multidisciplinary communications	

Fig.1- Fundamental relationship between a design tool and a design methodology

uncatered - for factors, reconfiguration or resubstitution. This quite often necessitates the evaluation of control and manipulation of the modulatory constituents [16]. Causal feedback is also an indication of possible causal conflicts within the structure. So the designer and the design team can obtain a constant feedback from the process of synthesis. This improved means of communication also allows them to take advantage of their intuitive reasoning in a directed and enhanced fashion. The failure of many designed systems to satisfy their initial requirements is often a direct consequence of ill - set - out initially proposed structures.

The information fed back to the designer through this recursive synthesizing pattern could, if the situation arises, direct attention towards possible necessary modifications in the structure of the design problem. The individual members of the design team in a mechatronic environment [9] would thus be given the opportunity to adopt a complete overview of the design, to understand and appreciate the entire structure of the system as opposed to designing sub-systems in isolation.

Therefore, the analytical structure for synthesis of mechatronic systems presented here proposes the causal synthesis to take place independent of any disciplinary governing rules and laws. The concept of Ideal Conceptual Design (ICD) has thus been presented so as to place the highest degree of integrity on the technical aspects of the design problem. Since the synthesized system is based on causal interactions within the structure of functional connectivity, the system would be valid and portray deterministic characteristics in every energetic sphere. Here the ICD primarily relies on the mathematical isomorphisms [18] amongst systems encountered in the reductionist approach to system description. Such justifiable analogies are based on generalisations originating from well - founded theries of general systems which have led to formulation of system analysis techniques like that of Bond Graphs. Here the ICD adopts the Bond Graph technique [19] as a design tool, from which any design produced would by definition be physically realisable. But to achieve physical realisation, the ICD must first be made into a concrete form in one or many energy domains (Fig.2).

Assertion of disciplinary governing constructs on to the ICD forces the model to leave the associated with this and other similar attempts rendered the propositions no advantage for designers or design teams. The design system that performed the design process includes designers who are actively participating through design information and its management. The transformation called designing, preferably takes the form of a sequence of any number of mappings from a more abstract form of a model to a more concrete form [8]. Each mapping is followed by a series of other design operations, including evaluation, selection, improving and quantifying the most promising proposals to carry the design forward to the next phase. Such generalised conclusions are no more than generic statements and have no real practical value in real time design environments. There are two distinct causes for lack of a generalised design methodology: an unproductive adoption of analogies leading to generalizations, and the difficulties in the structuralisation of the most instrumental segment of the design process, namely, the synthesis.

In today's increasingly mechatronic environments [9], synthesis is the last bastion of human ingenuity. Synthesis has been considered the heart and the nucleus of design [10]. It is here that creativity and intuition along with knowledge and experience come together to perform at the height of human abilities. Well understood, as they are, intuition and creativity possess almost indefinable and non - quantifiable characteristics [11]. This lays open the concept of synthesis to subjective interpretations. Consequently any structural or systematic development of the concept could seem a futile exercise. The problem is that free thought, defies any impositions which may be executed by a generalised methodology. However, for any such approach to be successful, a number of fundamental requirements must be met, (Fig.1).

Causal Synthesis

The concept of causal synthesis is based on the realisation that formalisation can have only a limited scope; here the emphasis has been placed on the concept of directed creativity as opposed to mechanisation of the thought process. This is achieved by allowing intuition to take advantage of a functional criterion supported by the causal laws [12]. If intuition requires a measure of how well the designer can "feel" the problem, then this feeling would require a point of reference. The relationship between this reference and intuitive decision will then manifest itself in the form of a combination of knowledge and experience. However knowledge and experience are primarily disciplinary conjectures. It is here that causality, with its inherent independency of the energy domain, as its intransigent principle, enhances intuitive reasoning. This is the only morphology that can prevail over the enigma of generalisation. In summary,"directed synthesis has all the propertise of free thought". The introduction of causality at the early stages of synthesis [13,14], would thus ensure adherence to underlying laws of physical sciences. Causal synthesis permits decisions to be made on the level of approach to system composition; that is, discrimination as to whether scrutinise the system on a wholistic basis or to study the isolated constituents [15]; whether to treat the system as a black box and study its relation to the environment, or to look at individual constituents and the manner by which the system is constructed. The recursive reticulation process responsible for bridging the gap between wholistic and constitutive synthesis, however, takes advantage of the concept of causal feedback.

Decomposition of the black box into appropriate functional connectivity [16], may not be a simple task. Emphasis on preferential causality [15,17], in conjunction with the properties of junction structures directs designer's attention to any one of the compensatory measures such as, further expansion of the model by introduction of

Nondisciplinary Synthesis in Mechatronics Utilizing Bond Graph Techniques

Ahmad Reza Arshi
Assistant Prof.

Biomedical Engineering Department
AmirKabir University of Technology

ABSTRACT

The newly forming concept of design science requires an analytical structure for the core of its discipline. For this, a unifying general methodology is necessary. Any generalisations would, however, embrace the concept of synthesis as well, thus rendering the proposed methodology ineffective. The approach adopted here is to take advantage of causal structures so that any proposed functional connectivity would be valid outside the paradigm of any one energetic mechatronic discipline. The technical merits of an analytical non-disciplinary approach to synthesis can be evaluated against a set of fundamental energetic constraints. The consequence of synthesis is further allowed to manifest itself in mechatronic systems.

Introduction

Design science [1,2] is an anthology of interdisciplinary Knowledge about design. It permits a scientific and coherent exposition of design activities, outside the framework of isolated paradigms of sciences. It is norished by the morphologies encountered in design processes [3], and methodologies and establishes the foundation stones for rational systematization of designer's activities. Design science contains the necessary falsifying fundamentals [4], which ensure adherence to the intrinsic ethos of a science. However, for the concept of design to portray a cohesive structure, as a credible discipline [5], two essential ingredients are necessary; first, the recognition of the contributory common patterns originating from various fields of activity and second, is the existance of a formal structure upon which the individuality of this newly forming discipline could be founded [4].

The goal of this paper is to achieve the latter by taking advantage of the former. That is to introduce a rational framework and a systematic approach to design; to produce a design methodology as the fundamental step towards mechatronic implementation of design science, to induce perception of large-scale connections, and to encourage the understanding and adoption of wholism as a principle. It also helps to recognize and absorb those system analogies and relationships that are instrumental within the concept of a general system design methodology. A wholistic study of engieering design as an important part of design science directs all unifying attempts towards the content of design process. The sequence and structure of operations in a design, its components and relationships, any systematic or procedural aspects, creative and intuitive factors and many other factors will contribute to form the skeleton of a systematic design process.

Systems Approach

The traditional systems approach to systematic design [6,7] exhibits many inadequacies in providing an analytical structure for the design process. The overgeneralisations