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A STATE SPACE APPROACH TO THE MANAGEMENT OF CONCURRENT DESIGN TASKS IN THE DESIGN OF A SYMMETRICAL WOBBLE PLATE COMPRESSOR

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Abstract: *This paper discusses how state space control concepts may be applied to the modelling and control of coupled, concurrent design tasks subjected to unexpected, dynamic disturbances. The Homogeneous State Space (HSS) model determines the natural response shape of the design process and predicts the number of iterations before all the design tasks are completed, while the Non-Homogeneous State-Space (NHSS) model precisely monitors and controls the stability and the convergence rate of each design task. The amount of additional work or resources required by each task at every stage of iteration can be determined; this facilitates workload distribution and resource allocation in design task planning and scheduling. A case study of the design of a new symmetrical wobble plate compressor is discussed to validate the proposed models in monitoring and controlling the stability of design tasks under the influence of unexpected disturbances.*

1. INTRODUCTION

The design of a complex product often involves inter-related specialist tasks. The interdependencies among design tasks give rise to complex information flows as the execution of a design task may create new information or conditions that affect other interdependent tasks. As all the coupled tasks are executed concurrently, design decisions made using incomplete or imperfect information are re-visited in what is termed *design iteration* [1]. There are several reasons for this. Firstly, rework is clearly necessary if the tasks which were completed earlier are not compatible with the new information generated by the later tasks. Secondly, external factors may have caused an un-anticipated change to the design objectives or parameters, over which the designer has no control. It is an established fact that design iteration increases cost and lengthens the lead-time of product development. Design iterations were found to account for an average of 33% of total project development time in Intel Corporation's semiconductor division [2]. Consequently, the modelling and analysis of design iteration is of great importance in the management of design projects.

Many process models have been developed to represent the design process. One popular representation is the *directed graph* (digraph) [3] which consists of nodes, representing the tasks, connected by arcs or directed lines, representing directed information flow. These arcs reflect the dependencies between the connected tasks. Another common graphical representation is *PERT/CPM* by which the 'critical path' of a project and the most optimistic completion time may be ascertained [4]. The Structured Analysis and Design Technique SADT [5], [6] which later evolved into the IDEF representation [7], is more formal than the digraph representation. *IDEF* models Computer Integrated Manufacturing (CIM) and Concurrent Engineering (CE) activities through a sequence of activities and relationships among them. The *Petri net* and its derivatives, applied most commonly to computer and manufacturing systems, verifies if a process is feasible [8]. Agent-based simulation tools such as *Virtual Design Team* (VDT) [9] assess the effect of the structure of an organisation on process execution. However, these methods cannot explicitly display circuits of information or iterations and can only efficiently process a limited number of tasks or activities.

The compact *Design Structure Matrix* (DSM), first introduced by Steward [10], depicts the task dependencies and the design iterations or information loops in a matrix form. The DSM has been widely applied in real engineering projects, for example, automotive brake system design [11], semiconductor [1] and jet engine design [12]. It has also been adopted widely in modelling engineering design tasks [13], [14] in the integrated analysis of engineering design management [15], [16], [17], and in design iteration analysis [18], [19].

Based on the DSM, Smith and Eppinger [20] identified the 'controlling features' of concurrent, coupled design tasks, i.e. those elements of a coupled design problem which require the greatest number of iterations to reach an acceptable solution. They postulated a numerical DSM called the Work Transformation Matrix (WTM), in which the measure of the strength of dependency between tasks is the percentage of rework created for one task by work performed by other coupled tasks. Although McDaniel [21] expanded the WTM to test the impact of different work policies on reducing the lead-time of a design process, it's effectiveness in the face of unexpected disruptions is unknown. Yassine et al [22] extended McDaniel's model to the systems (managerial) level, by managing the exchange of information among coupled design tasks. Although their model can accommodate internal disruptions such as policy changes, it remains a descriptive representation of the entire design process with no quantitative means of control.

These and other analytical methods are inadequate in modelling and controlling design processes which are dynamic and subject to unexpected influences. For instance, an external disturbance such as a competitor's initiatives may necessitate a re-examination of the entire design project in order to reduce costs or shorten the product development cycle time. Resources may have to be re-allocated among the various design tasks to achieve this goal. Thus, it is imperative for managers to be able to monitor and control design tasks in an uncertain, volatile global business environment. This paper discusses a generalised state-space control model of coupled, concurrent design tasks proposed to model and control coupled, concurrent design tasks subjected to unexpected disturbances.

2. THE STATE EQUATIONS FOR CONCURRENT DESIGN ITERATION

A design process comprising n tasks is represented as an n x n design structure matrix (DSM). Readers may refer to several literatures on how to read a DSM [1], [10], [13]. Concurrent design iteration can be expressed in the state equation as follows

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{B}\boldsymbol{u}(k) \qquad (1)$$

where the index k, the discrete-time variable, represents a finite number of stages of iteration. Each state variable x_i in the state vector $\boldsymbol{x}(k)$ indicates the status of task i at the kth stage of iteration. The state matrix $\boldsymbol{A}$ is a DSM the elements of which quantitatively denote the interdependencies of tasks, while the input matrix $\boldsymbol{B}$ represents the proportion of common resources shared by two or more tasks. $\boldsymbol{u}(k)$ denotes the control input required by tasks in order for the entire design project to arrive at the desired states. The control input of a task u_i may be the additional resources required by a design task to cope with or to reduce the amount of rework. These additional resources can be acquired through overtime work, hiring new staff, temporary help, outsourcing, technology acquisitions, etc. The unit of measure of a task's state can be one of several, e.g. cost, engineering times, the number of design actions, the amount of rework, etc. As the volume of work is chosen as the unit of measure of state in this paper, the state matrix $\boldsymbol{A}$ is a Work Transformation Matrix (WTM), similar to Smith and Eppinger's [20]. Each of the entries a_{ij} in the WTM $\boldsymbol{A}$ implies that, as one unit of work is accomplished by task j, a_{ij} units of rework are created for task i. $\boldsymbol{A}$ therefore embodies the degree of coupling among the inter-dependent tasks. The state vector $\boldsymbol{x}(k)$ is an n-vector, where n is the number of coupled design tasks. Each element of $\boldsymbol{x}(k)$ represents the fraction of the initial work that each task must accomplish at stage of iteration k. Equation (1) shows that the volume of work that has to be done by a design task is a linear combination of the amount of work generated by other coupled tasks in the preceding stage of iteration *plus* the effect of the control input.

The open-loop system described by equation (1) is called the *Non-Homogeneous State-Space* (NHSS) representation of concurrent design tasks. It is called non-homogeneous because external inputs are modelled. A system is said to be homogeneous if there are no external inputs and the system response is due only to initial conditions. The *Homogeneous State-Space* (HSS) representation of coupled, concurrent design task is expressed as

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) \qquad (2)$$

The following three assumptions are made before linear algebraic analysis can be performed [20][11]:

- All tasks are executed concurrently at every stage.
- The quantum of re-work of a task is a linear function of the work done by other coupled design tasks.
- The elements of the state matrix (i.e. the strength of dependency of tasks) do not vary with time.

2.1 Stability of tasks

The stability of the homogeneous or undisturbed system may be gauged from the eigenvalues and eigenvectors of state matrix $\boldsymbol{A}$. The eigenvalue matrix $\boldsymbol{V}$ has n diagonal elements, each of which, λ_n, represents an eigenvalue of the $\boldsymbol{A}$ matrix, assuming n distinct eigenvalues. The n x n eigenvector matrix $\boldsymbol{S}$ consists of column vectors $\boldsymbol{S_j}$ (j = 1, 2… n) each of which is an eigenvector which is associated with one of the eigenvalues λ_n (e.g. $\boldsymbol{S_1}$ with λ_1). An eigenvector embodies a *mode shape* of the system [23]. In concurrent design iteration, the mode shape is also known as the *design mode* [20]. A design mode is a group of intimately related design tasks which create significant work, directly or indirectly, for each other. The superposition of all the mode shapes makes up the response of the system [24]. Each mode shape ($\boldsymbol{S_j}$) is represented by the relative fractions (i.e. the elements) s_{ij} (i = 1,2,…n) in a column, each of which corresponds to a state variable (i), or to a task's state. The eigenvector corresponding to each eigenvalue characterises the relative contribution of each of the tasks to the total work. The most slowly converging or diverging design mode, i.e. the critical design mode, corresponds to the eigenvalue with the largest real value. In concurrent design iteration, everything hinges on the critical design mode (or the critical eigenvector) while the slowest task is the task with the largest number in the critical eigenvector [25].

While the eigenstructure of the state matrix reveals the dominant response shape of tasks, the location of an eigenvalue in the complex plane reveals the expected type of response. From the location of the eigenvalue in the complex plane, the system can be ascertained to be stable (convergent), unstable (divergent), or oscillatory (recurrent re-work) [25]. Obviously, convergent tasks with steady workload are most desirable because they are stable. A state matrix's eigenstructure gives some insight into the stability of concurrent design tasks. The natural (or undisturbed) response of the system can be determined even before the first design task begins. A natural response indicates the progress of a design process over time without any external disturbance. In reality, however, real life design processes are subject to unexpected disturbances. Thus, it is essential to monitor and control all design tasks simultaneously.

2.2 Control structure of concurrent design

The HSS concept essentially models the natural response of coupled, concurrent design tasks without any disturbance. When the design tasks converge to a satisfactory completion in a finite number of iterations, the design project is said to be stable. Even though the design project may be stable, the convergence rate of the design tasks may be slower than expected because of limited know-how and resources. Smith and Eppinger [20][11] propose manipulating the task dependencies of the WTM $\boldsymbol{A}$ to improve stability but as the elements of the state matrix represent the task dependencies, these are not easily changed since these dependencies are governed by the causal connection in information flow. Besides, it is both tedious and error-prone to try to bring about stability in the face of dynamic disturbances. Smith and Eppinger also suggested shortening the lead time by the infusion of more resources. Intuitively, the allocation of more resources can improve the convergence rate of design tasks, but this immediately raises the question of the amount of additional resources and the impact of disturbances even after these additional resources are assigned to the design tasks. The authors therefore propose employing *state feedback control* (SFC) in the NHSS model to overcome both these difficulties.

As discussed in Section 2.1, the stability of a system depends on the eigenvalues of the state matrix. In order to achieve the desired stability, an appropriate *resource gain matrix*, $\boldsymbol{K}$, is defined. In the case of concurrent design iteration, the $\boldsymbol{K}$ matrix encompasses the degree of control exerted by one task on others [26].

The control input of an open-loop system shown in equation (1) is assumed to be a vector:

$$\boldsymbol{u} = -\boldsymbol{K}\boldsymbol{x}(k) \qquad (3)$$

where $\boldsymbol{K}$ is the resource gain matrix.

By substituting equation (3) into equation (1) and assuming that resources are not shared among the various tasks (i.e. the $\boldsymbol{B}$ matrix is an identity matrix), the closed-loop state feedback equation becomes

$$\boldsymbol{x}(k+1) = \boldsymbol{A}^*\boldsymbol{x}(k) \qquad (4)$$

where $\boldsymbol{A}^* = (\boldsymbol{A} - \boldsymbol{I}\boldsymbol{K})$, $\boldsymbol{I}$ is an identity matrix.

The stability of the closed-loop state feedback system (4) depends on the eigenvalues of the $\boldsymbol{A}^*$ matrix, notably the appropriate gain matrix $\boldsymbol{K}$. The authors have developed an algorithm to derive the eigenstructure (and therefore the gain matrix $\boldsymbol{K}$) that assures the desired performance of the design tasks. The algorithm first transforms the state matrix $\boldsymbol{A}$ into another transformation matrix the elements of which are the eigenvalues that determine the desired performance of the design tasks. These eigenvalues are determined from the desired completion state of the tasks, $\boldsymbol{x}_d$ and the corresponding number of iterations, $k_{d.}$ The details of this algorithm may be found in [26].

The state equation (4) can be rewritten as

$$\boldsymbol{x}(k+1) = \boldsymbol{A}\boldsymbol{x}(k) + \boldsymbol{u}(k) \qquad (5)$$

The state of the design process at the (k+1)th stage of iteration, $\boldsymbol{x}(k+1)$, is now the summation of the homogeneous state $\boldsymbol{A}\boldsymbol{x}(k)$ and the control input $\boldsymbol{u}(k)$, which is a function of the preceding state $\boldsymbol{x}(k)$ and the resource gain matrix $\boldsymbol{K}$. When the state of the preceding stage k deviates from the expected value because of some disturbance, the control input $\boldsymbol{u}(k)$ and the resource gain matrix $\boldsymbol{K}$ can be revised to cope with the deviation. A case study of the design of a compressed natural gas (CNG) compressor is discussed to demonstrate the applicability of the proposed models in analysing, monitoring and controlling design tasks under the influence of unexpected disturbance.

3. DESIGN OF A SYMMETRICAL WOBBLE PLATE COMPRESSOR: A CASE STUDY

An international petroleum company and Universiti Teknologi Malaysia collaborated concurrently to design a compressor of CNG for refuelling purposes. A new concept of symmetrical wobble plate was employed in the compressor design. A picture of the compressor's conceptual design is shown in Figure 1. While the university focused on the mechanical aspects of design, the company concentrated on the electrical and electronic aspects. This case study focuses on the mechanical aspects, from planning to delivery of the first prototype. The authors define a design task as beginning with the definition of functions and specifications of the artefact to detailed design, analyses and final prototyping.

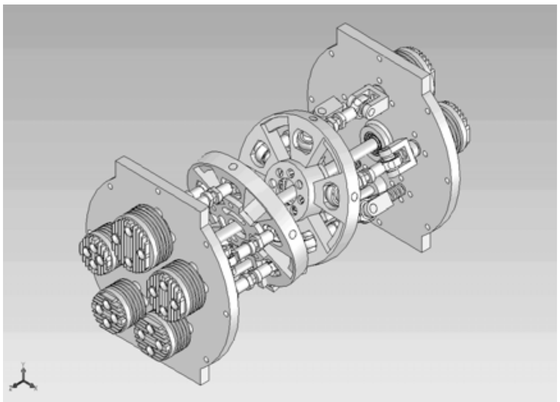

Figure 1. *Conceptual design of the symmetrical wobble plate compressor.*

The design of mechanical system comprises 12 subsystems: Wobbling Mechanism, Transmission Mechanism, Compression System, Driver System, Gas Dynamic, Cylinder & Casing Assemblies, Lubrication system, Maintenance, Anti-rotating Mechanism, Storage & Piping System, Thermodynamic & Cooling and Motion work. The 12 subsystems were designed concurrently as the 8 design engineers from manufacturing, R&D and mechanical engineering were known to be able to work with each other. These 8 engineers were the main resources assigned to the project. The design project started on the 1st week of August 2002 and was scheduled to be finished with the delivery of the prototype at the end of September 2003 on week 60.

3.1 Homogeneous state space (HSS) modelling and analysis

The 8 engineers were interviewed for all the information necessary to construct a numerical Design Structure Matrix (DSM). For instance, they were asked to spell out the precedence relationships among the 12 design tasks and to estimate the cycle time of a complete iteration of each task. An iteration is a design cycle during which some design action is taken to finish the work that was generated by other tasks during the immediately-preceding stage of iteration. In a *complete* iteration, the remaining work is 100%; for example, at the initial execution of a design task. A state matrix, similar to the WTM, was obtained as shown in Table 1. In Table 1, the element in 3rd row and 1st column means that task 1's relationship to task 3 is such that task 3 (Compression System) has to redo 30% of its work after task 1 (Wobbling Mechanism) undergoes a complete iteration. An initial HSS analysis of all 12 design tasks can now be undertaken. The engineers were asked to record the time taken by each and every task to finish each iteration, and the proportion of remaining work after every stage of iteration.

3.1.1 The natural response and convergence rate of tasks

The state matrix's eigenstructure predicts a stable and convergent natural response of all 12 design tasks (see Figure 2). It can be seen from Figure 2

Table 1. *State matrix of the symmetrical wobble plate compressor design*

Task name	Time (Hour)	ID	1	2	3	4	5	6	7	8	9	10	11	12
Wobbling mechanism	140	1	0	0	0.20	0.04	0.20	0.03	0.04	0	0.04	0.01	0	0.05
Transmission mechanism	140	2	0	0	0	0.05	0	0	0.06	0	0	0	0	0
Compression system	336	3	0.30	0	0	0.02	0.24	0.01	0.14	0.07	0	0	0	0
Driver	84	4	0.16	0.06	0.14	0	0.05	0.01	0.09	0.05	0.01	0.01	0.07	0.09
Gas dynamic	280	5	0.03	0	0.05	0.03	0	0.03	0.17	0.17	0	0.01	0.17	0
Block & casing	196	6	0.02	0	0	0.01	0.03	0	0.04	0.03	0	0.01	0.05	0
Lubrication system	420	7	0.16	0.06	0.14	0.08	0.27	0	0	0	0	0	0.20	0.05
Maintenace	140	8	0	0.15	0.07	0	0.08	0.05	0	0	0	0.03	0.17	0
Anti-rotating mechanism	112	9	0.02	0	0.04	0.01	0	0	0.04	0	0	0	0	0.25
Storage & piping system	420	10	0.02	0	0.03	0	0.01	0.01	0	0.03	0	0	0.05	0
Thermodynamic & cooling	560	11	0.07	0	0.10	0.07	0.22	0.07	0.40	0	0	0.05	0	0
Motion work	224	12	0.15	0.08	0.07	0.09	0.21	0	0.20	0	0	0	0	0

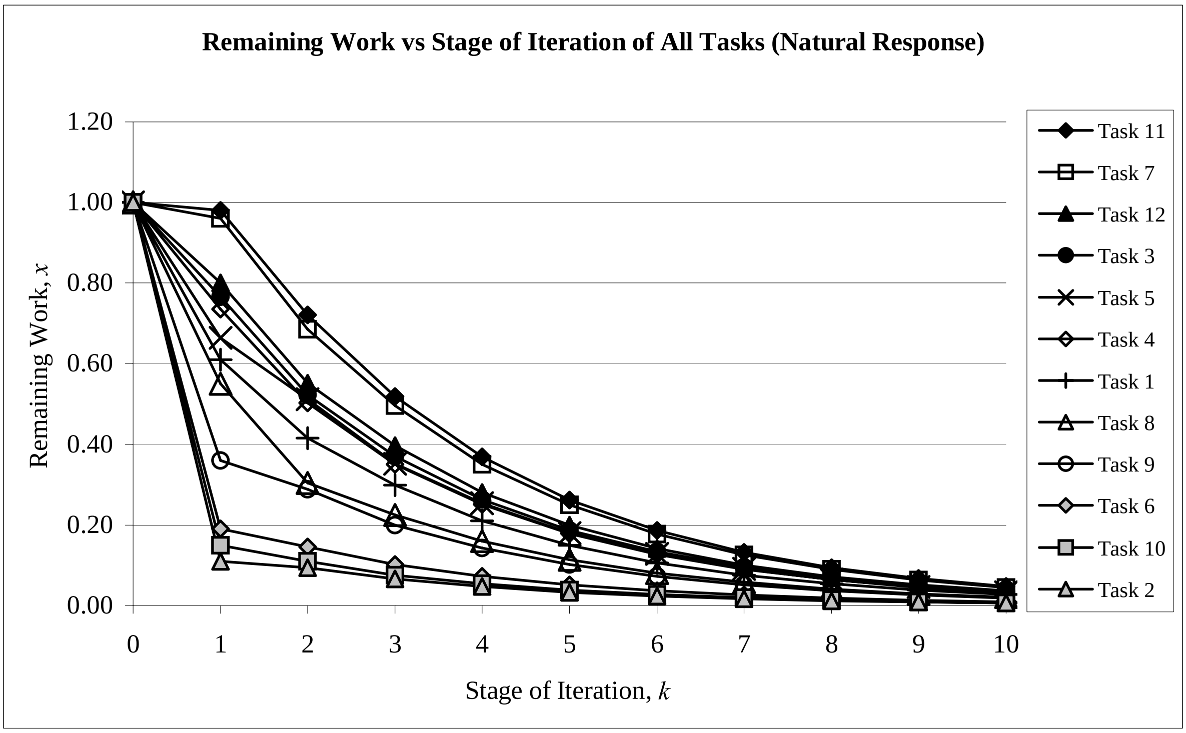

Figure 2. *Natural response of the symmetrical wobble plate compressor design*

that, assuming that all 12 design tasks started off with 100% of work, the remaining work of all tasks decreased after every stage of iteration. According to the critical eigenvector of the state matrix, the slowest task was task 11 (Thermodynamic & Cooling) with the largest value in the critical eigenvector – 0.463. The earliest possible completion of the entire project therefore hinges on task 11. Table 2 shows the predicted natural response of the entire mechanical system design, given that task 11 is the slowest-converging task.

The entire mechanical system design is deemed to be completed when the alpha prototype is delivered, i.e. by week 60 (the 4th week of September 2003). However, from Table 2, the remaining work of task 11 by week 60 is less than 9.5%. If delivery is enforced on week 60, this means that only 90.5% of task 11 will have been completed. Thus, the completion state of task 11 was set at $x_{c11} = 0.095$. That is to say, at the time of scheduled completion, the remaining work of each and every of the 12 design tasks should not exceed 9.5%. Since the first prototype was built with production-intent parts, i.e. parts having the same geometry and material properties as those in actual production, but not necessarily fabricated by the same manufacturing process, 9.5% of remaining work is considered acceptable. The convergence rate of each task, from the slowest to the fastest, is shown in Figure 2. Task 11 was the slowest as it was strongly relied on several tasks such as task 3 (Compression System), task 5 (Gas Dynamic) and task 7 (Lubrication System), while task 2 (Transmission Mechanism) was the fastest since it only slightly depended on task 4 (Driver System) and task 7 (Lubrication System).

Table 2. *Natural response of the design process*

Stage of Iteration k	Slowest task's remaining work (%)	Cumulative time elapsed (hours)	In week #	Status
0	100	560	14.0	
1	98	1108	27.7	
2	72	1512	37.8	
3	52	1803	45.1	
4	37	2010	50.3	
5	26	2157	53.9	
6	19	2261	56.5	
7	13	2336	58.4	
8	9.5	2389	**60.0**	Planned completion

A disturbance was encountered in the course of the project. The disturbance happened in week 51 when the design team was required by the company to change some design specifications, particularly the capacity of the compressor and the refueling time. Faced with the unexpected disturbance, the HSS had to re-assess the completion date of the project. The change of design specifications caused the project to languish for 4 months in order to redesign and catch up to the previous design status.

The response of the overall project with the disturbance is tabulated in Table 3. Compared to the natural response in Table 2, the disturbed response requires one more stages of iteration. The disturbance occurred after the 4th stage of iteration, and so the remaining work of all tasks after the 4th stage of iteration was not attempted in the 5th stage of iteration. Instead, this remaining work was attempted in the 6th stage of iteration, giving rise to the 4 months delay. From Table 3, we see that the disturbed project can only be finished in week 75.7.

Table 3. *Response analysis of the entire project after disturbance*

Stage of Iteration *k*	Slowest task's remaining work (%)	Cumulative time elapsed (hours)	In week #	Status
0	100	560	14.0	
1	98	1109	27.7	
2	72	1513	37.8	
3	52	1804	45.1	
4	37	2010	50.3	
5	26	2650	66.3	Change of specifications- took 4 months to redesign and catch up to the previous state
6	26	2797	70.0	
7	19	2902	72.5	
8	13	2976	74.4	
9	9.5	3029	**75.7**	Predicted completion after disturbance.

It should be remembered that no extra manpower resources were employed to expedite the design project, because there were always 8 engineers in the design team, although overall, the company could have hired an additional engineer. That being the case, it is of management's interests to understand how additional resources would help in minimising the effects of disturbance. The next section shows how the NHSS concepts may be used to analyse the effect of additional resources deployment to all tasks on: (i) faster time to completion, and (ii) higher quality of design decisions. Hence, 2 scenarios will be discussed: scenario A, additional resource deployment to all tasks with fastest time to completion; scenario B, additional resource deployment to all tasks with highest quality of design decisions.

3.2 NHSS control and analysis

To see how the NHSS concept can be applied to control the design of the symmetrical wobble plate compressor in the face of unexpected external disturbance, 2 scenarios were simulated. Additional resources were employed to ensure that progress was achieved at the desired states. From Table 2, it can be seen that the project is scheduled to be completed at the 8th stage of iteration, but after the disturbance, a hopeful completion date appeared to be at the 9th stage of iteration (see Table 3). The desired completion states, x_d, and the desired stage of iteration, k_d, are summarise in Table 4 for the 2 scenarios.

The desired outcome of scenario A is to complete the entire design project within the contractual deadline. This is often crucial, especially for time-sensitive products or new products. In contrast, the metric in scenario B was result-concerned, where the quality of design decisions was more important. To increase the chances of better quality of design decisions, more iterations should be allowed for more deliberations. Fewer iterations entail a greater risk that the design will not converge to the desired target, or, at best, yield designs of poor quality. More iterations improve the chance that the design will converge to acceptable multi-attribute performance levels [27]. After the disturbance which happened at the 5th stage of iteration, the remaining work of the five slowest tasks, i.e. tasks 3, 5, 7, 11 and 12, exceeded 18% of their initial work. If these tasks were forced to stop immediately after two stages of iteration like in scenario A, the quality of the design decisions might not be as good as if three more stages of iteration were permitted. As will be seen later, the progress of the controlled design tasks in scenario B was even faster than in the case of the uncontrolled disturbed response; however, more time is needed compared to scenario A. This situation is common to the design of customised and complex products, like assembly robot arms, manufacturing machines, automobiles and aircrafts, where high precision is an important design requirement. The 2 scenarios demonstrates how the state feedback control of NHSS can reliably predict the amount of extra resources needed to improve the disrupted design process of the symmetrical wobble plate compressor.

Table 4. *The 2 possible scenarios of project completion after the disturbance*

Scenario	Desired outcome	Desired completion state, x_d, and desired stage of iteration, k_d
A	Project completion by 5 weeks after the disturbance (change of specifications), i.e. by week 71.3.	The desired completion states of tasks are the same as those for the natural response, x_c, e.g. the remaining work of task 11 is 9% when the project is assumed completed. However, the number of iterations to completion is 7 or about 71.3 weeks (2850 hours). This contrasts with the 9 iterations for the uncontrolled disturbed response. $x_{dA} = x_c$, $k_{dA} = 7$
B	Project completion by 3 more iterations after the disturbance.	The desired completion states of tasks are the same as those for the natural response, x_c, but the number of iterations to completion is 8, i.e. 3 stages after the 5th stage of iteration which was when the disturbance happened. $x_{dB} = x_c$, $k_{dB} = 8$

3.3 Discussion of results

The NHSS approach analysed the volume of rework of each task that needs to be reduced at each stage of iteration for the entire design project to be completed on time. The rework can be reduced by infusing additional resources in the precedent stage of iteration. For instance, employing extra manpower or out-sourcing design tasks or investing in additional equipment. In the design of the compressor, manpower was the sole resource considered. For simplicity sake, the authors assumed that the amount of resources is proportionally related to the volume of work. This is normally true when resources are adequate. In some other cases, however, the relationship is nonlinear. A common example of a nonlinear relationship is when the resources needed by a task are insufficient to process the increased amount of information generated by other tasks. This typically occurs in design of innovative, new products, or products to be used in conditions which are not fully understood; for example, a new hyper-sonic aircraft, a nano-fabrication device, etc. At any rate, an experienced design manager should know the relationship between the amount of resources and the volume of work. If the volume of rework that needs to be reduced, $\boldsymbol{w}$, is known, the additional resources can be determined. In the NHSS analysis, the unit of $\boldsymbol{w}$ is the unit of the state variable, while the amount of additional resources, $\boldsymbol{a}$, is a percentage of the initial resources, $\boldsymbol{r}$. As the 8 engineers worked on all 12 design tasks, the initial resources available to each task, $\boldsymbol{r_i}$ ($i = 1, 2, \ldots, n$; $n = 12$) was 8/12 of the wage cost of an engineer (based on an 8 hour work-day and a 5-day work-week), assuming that each design task receives the same amount of resources initially.

3.3.1 Scenario A

In this scenario, all the available manpower resources were deployed with the goal of completing the entire design project in the shortest possible time. Table 5 shows the results of NHSS analysis. The second column reveals the volume of rework that needs to be reduced for each task, w_i, while the right-most column shows the amount of additional resources needed by each task, as a percentage of total additional resources needed by the entire project. The total extra resources needed, as a fraction of initial resources, T_w is the total of w_i. In this case, T_w is 0.6 (see Table 5). If we multiply T_w with the initial resources of a task, r_i we obtain the total additional resources needed to expedite the project, T_a, i.e. $T_a = r_i T_w = (0.67)(0.6) = 0.4$ of the wage cost of an engineer. In real life, T_a can be realised in several ways. For example, an experienced engineer can devote an additional 40% of his daily working hours (or about 3.2 hours) in re-examining and refining imprecise information. On the other hand, the company could deploy a new engineer whose effectiveness is reckoned to be about 40% of an experienced engineer's, and so would need to spend his entire working day on the project, or the entire existing design team of 8 engineers works an extra 5% (0.4/8= 5%) daily. If the eight engineers worked overtime, they can reduce the rework of tasks according to the figures in Table 5. Up to now, we have assumed that the additional work consumes as much resource as normal work. That is not always true. In fact, most times additional work consumes more resources than normal work because of the pressure of time and the attention to detail needed. However, in the subsequent scenario, the additional work is assumed to be the same as that of normal work so as to normalise the calculation. Table 5 also shows the additional resources to be allocated to each task. For instance, if 15% of T_a were allocated to the slowest task, task 11, 9% of its remaining work can be finished. If the engineers apportion their overtime hours according to the proportions of additional work shown in Table 5, the project can be completed 22 days earlier, i.e. by week 71.3, as Table 6 shows. Only the 6th stage of iteration needs additional resources. While completing the 26% remaining work at the 6th stage of iteration, additional resources are applied according to Table 5 so that the slowest task achieves 9.5% remaining work at the 7th stage of iteration.

Table 5. *Additional resources of scenario A at the 6th stage of iteration*

Task	Amount of rework to be reduced, w_i	Amount of additional resources needed, as a percentage of total additional resources
1	0.05	8.57
2	0.01	1.92
3	0.07	10.7
4	0.06	10.2
5	0.06	10.3
6	0.02	2.98
7	0.09	14.3
8	0.04	6.50
9	0.04	5.82
10	0.01	2.22
11	0.09	15.0
12	0.07	11.4
Total	0.6	100.00

Table 6. *Scenario A: Simulated response of entire project after the disturbance*

Stage of Iteration k	Slowest task's remaining work (%)	Cumulative time elapsed (hours)	In week #	Status
5	26	2650	66.3	Design change
6	26	2797	70.0	Additional resources applied
7	9.5	2850	**71.3**	Design project completed.

3.3.2 Scenario B

This scenario examines the impact of three more stages of iteration after the 5th stage. Table 7 shows the volume of rework that needs to be reduced at the 6th and 7th stages of iteration. The total additional resources required in the 6th stage of iteration, $T_{a,k=6} = r_i T_{w,k=6}$ = (0.67)(0.19) = 0.127 of the wage cost of an engineer; in the 7th stage of iteration, $T_{a,k=7} = r_i T_{w,k=7}$ = (0.67)(0.25) = 0.167 of the wage cost of an engineer. These numbers imply that the additional experienced engineer must put in an additional 12.7% of his daily regular working hours at the 6th stage of iteration, and 16.7% of his daily working hours in the 7th stage of iteration; or a new engineer, whose effectiveness is reckoned to be only 15% of that of an engineer in the team, is hired to work full-time, all-day, through stages 6, 7 and 8; or the design team of eight engineers puts in nearly half an hour of overtime daily. With the additional resources, the rework of each task after each stage of iteration should be reduced by as the amount shown in Table 7. Although the project converged slower than in scenario A, the project still finished faster than the case of uncontrolled response (see Figure 3). Fewer additional resources were needed in each stage of iteration compared to scenario A, although the overall total additional resources required may be more if more stages of iteration are allowed. This is understandable as scenario B took longer time to finish (246 hours) compared to the case of scenario A (200 hours). This is intuitively appealing to design companies with very tight resources. Although the net amount of resources may be more than scenario A's, the company can afford the piecemeal additional resources needed at each stage of iteration. In scenario B, the entire design project was successfully finished by week 72.4, i.e. 16.5 days faster than uncontrolled response (see Table 8).

Table 7. *Additional resources of scenario B at the 6th and 7th stages of iteration*

Task	Amount of rework to be reduced, w_i		Amount of additional resources needed, as a percentage of total additional resources
	6th stage	7th stage	
1	0.02	0.02	8.57
2	0.00	0.00	1.91
3	0.02	0.03	10.7
4	0.02	0.03	10.2
5	0.02	0.03	10.3
6	0.01	0.01	2.98
7	0.03	0.04	14.3
8	0.01	0.02	6.50
9	0.01	0.01	5.81
10	0.00	0.01	2.20
11	0.03	0.04	15.0
12	0.02	0.03	11.4
Total	0.19	0.25	100.00

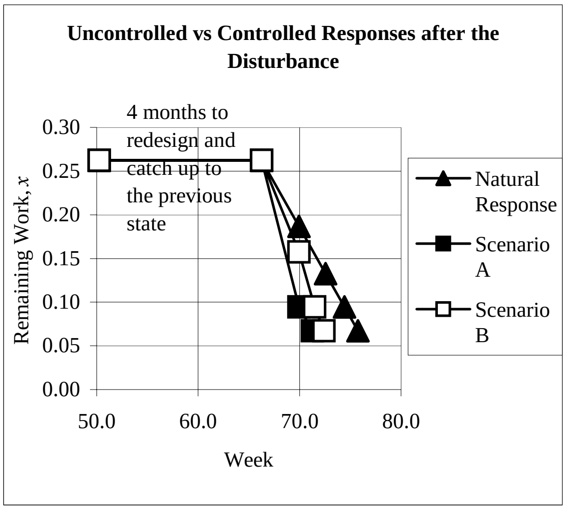

Figure 3. *Uncontrolled and controlled responses after disturbance*

Table 8. *Scenario B: Simulated response of entire project after the disturbance*

Stage of Iteration *k*	Slowest task remaining work (%)	Cumulative time elapsed (hours)	In week #	Status
5	26	2650	66.3	Design change
6	26	2797	69.9	Additional resources applied
7	16	2859	71.5	Additional resources applied
8	9.5	2896	**72.4**	Design project completed

3.4 Some comments on the additional manpower resources

The additional manpower resource discussed above can be realised in several ways. The new engineer joining the design team could be from another department or project, since it is impractical to hire a new person. However, this pre-supposes that such an engineer can be released from his current duties, and is as qualified and experienced as those in the design team. The second suggestion to hire a fresh, full-time engineer is arguably idealistic. The third suggestion for the entire design team to work overtime is by far the most plausible. However, one should guard against diminishing effectiveness from long hours at work. Thus, it can be seen that the NHSS analysis enables management to more precisely monitor and control the progress of a design project. Perhaps the biggest difficulty facing management is the extent to which it is familiar with the capabilities and limitations of the staff under its charge. Unless and until this is known with some certainty, the predictions of the NHSS will remain an ideal. The authors are confident that the case study discussed illustrates that the NHSS can be a formidable tool in the management of design projects. If human resource were the only resource considered in the analysis, then it is management's duty to be thoroughly conversant with the capabilities and limitations of the staff under its charge in order to derive the most benefit from the NHSS analysis.

4. CONCLUDING REMARKS

A generalised homogeneous and non-homogeneous state-space concept to model, predict and control the stability and convergence rate of coupled, concurrent design tasks is proposed. It can identify those tasks that consume a disproportionate amount of resources and time, that require many iterations to complete or that eventually run out of control, and potentially minimise the duration of the entire design process.

A case study of the design of a symmetrical wobble plate compressor is discussed to validate the proposed methodology. The homogeneous state space (HSS) model identified the slowest and fastest converging tasks and prescribed one additional stage of design iteration, when the entire design project was threatened by delay due to change of design specifications.

In the face of unexpected external disturbances, two scenarios were investigated in the non-homogeneous state space (NHSS) model to determine their effects on the quality of design decisions and the shortest time to completion. The various options for deployment of manpower were studied: hire a new engineer or work overtime. If overtime work alone were undertaken, the entire design of the symmetrical wobble plate compressor can be completed 22 days ahead of time. When three more iterations were allowed after the disturbance the project naturally converged slower than if there were only two extra iterations. Although the chances of better quality designs can be expected with more iterations, fewer resources were needed at each stage of iteration. However, the sum total resources consumed may be increased when more stages of iteration are allowed. This mode of design task management is good for companies with very tight resources and so can only afford piecemeal additional resources needed at each stage of iteration.

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