COMMAND AND CONTROL SYSTEMS—CHALLENGING THE PARADIGMS

Derek K. Hitchins

Abstract

Much of industry and the military customer are locked into a view of command and control which is challenged both by recent changes in the world order and by our advancing understanding of such apparently well-understood phenomena as decision-making. Do we really understand what constitutes a good decision? Is a good decision one in which large amounts of data are condensed into a form that can be easily assimilated by a senior decision maker? Or, is a good decision one that works? Are we, in other words, more concerned with process than outcome? For instance, the process of scaling up seems eminently sensible, and we are all aware of the advantages to be gained from so-called economies of scale. Why is it, then, that these economies so regularly fail to materialize?

We have learnt many lessons in reaching our present level of expertise in systems engineering. Or have we observed the lessons, but not really learned them? Are there inexorable pressures pulling us in the direction of technology for its own sake? As the environment about us changes, and it is changing very rapidly at present, our present, rather rigid, technological approaches may be inappropriate to address essentially human issues in a changing world. The future will place ever-increasing emphasis on C3 systems, but we must understand the real nature of the future situations and not simply assume that more of the same technology is the right answer. Warrior concepts suggest we need to think again. Policing within the framework of UN HCR and Peace Keeping organizations are already changing our viewpoints.

UNDERSTANDING DECISIONS

We are all aware of the relationship between decision-time and decision importance, i.e. the more important the decision, the less time is taken reaching it. This is a committee phenomenon, especially, with more time being spent on such issues as soft versus hard toilet paper than which word processing package to standardize upon or which manufacturing investment to make.

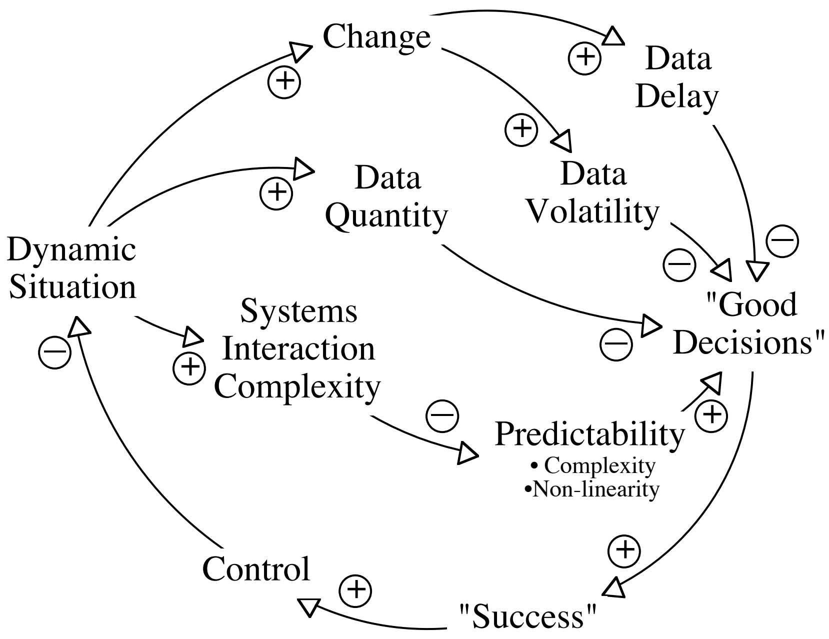

Figure 1 What is a "Good Decision"?

The process and effectiveness of individual and group decisions in a rapidly changing environment is little understood (see Klein *et al*, 1986 and Klein 1988). What is a "good decision"? As Figure 1 suggests, dynamic situations promote: change; increased amounts of data; and faster, more complex, even chaotic interactions between systems.

(As Shannon's information theory proposes, data are worthless unless they describe change). Such complex interaction may defy prediction: it is not that prediction is difficult; the outcome may be genuinely "unknowable". Economists have faced this dilemma for centuries—they make a living by predicting the unknowable with great accuracy. Weather-men are in the same arena. So, too, are generals. And our captains of industry. At best, we may be able to identify and even influence long-term trends, while mid-term prediction may be truly beyond us.

The time-horizon of predictability is short in changing, complex environments, tending to emphasise fast response "on-the-fly". Game theory suggests that, in a dynamic environment, there is advantage in making a *swift* decision, especially one that reduces the enemy's options. A comprehensive decision may take longer to formulate *and* may result in the decision being highly predictable to the enemy. Perhaps the best that we can say is that a good decision is one where the out-turn favours our intention—perhaps good decision-makers are lucky, rather than smart. Napoleon was once asked what, in his opinion, was the main attribute of a good general. He is said to have replied: "That he be lucky."

SCALE EFFECTS

Evolutionary Acquisition

Difficulties arise as systems become larger. We seek economy of scale, but quite often it seems to elude us in the event. Experience shows that trying to specify and build a large system from the word "go" is unlikely to be the most successful approach. There are several ways to address the problem: given an overall design, we might seek to acquire the whole system piece-by-piece, the so-called "evolutionary-acquisition" approach. The potential benefits of such a method are evident: expenditure is manageable; problems can be identified and remedied as they arise; etc. The pitfalls should be evident, too.

Evolutionary acquisition must, by its nature, be a protracted process, during which time the environment and the need will change. So, the system concept should change, too. But the parts that have already been delivered may be unable to change, resulting in later additions becoming more and more *ad hoc* and complex as they seek, not only to fulfil their originally-intended function, but to accommodate the requisite modifications to earlier deliveries. The result may be less a system, more a mess—it certainly stands little chance of being optimum, and later additions will prove more and more difficult. Evolutionary acquisition depends fundamentally on the environment remaining substantially constant—and that is a rare situation.

Scaling Up

Changing environments require, instead, rapid building of systems which can also be adapted once in use. Prototyping is a useful notion, and one that is gaining credibility. It is far from knew, of course. The Pharaohs of Ancient Egypt had a series of pyramids built over a period of some 100 years, starting with Zhoser's stepped pyramid at Memphis and culminating in the Great Pyramid of Cheops at Saqqara. To this day, the process of learning and adaptation is quite evident in the variety of pyramid designs leading from the first to the last which, even today, stands as the largest building ever constructed by man.

Prototyping is a valuable approach. It enables us to understand complex parts of a system and the interactions between such complex parts. However, it may not always be simple to scale-up from the prototype to the full thing, particularly for human-activity systems. Figure 2 illustrates the point.

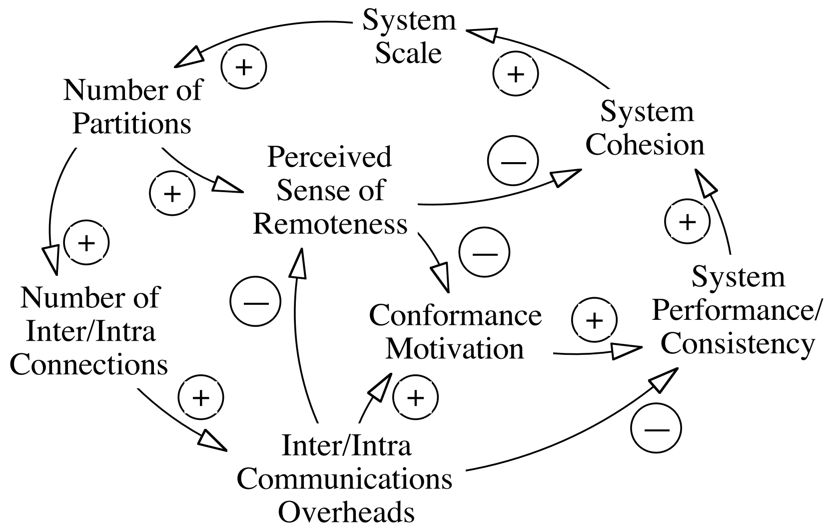

Figure 2 Economy of Scale?

As the system grows, two things happen: the number of partitions within the system increases; and parts of the system become mutually more remote. Both phenomena necessitate increasing internal energy to maintain system coherence, to the detriment of external effectiveness. In the case of partitions, for example, the number of potential relationships increases approximately as the square of the number of sub-systems. How perceived remoteness behaves is more difficult to define, but we are all aware of "large company impersonality".

SYSTEMS ENGINEERING

Re-learning Old Lessons?

It seems that we have new lessons to learn, but perhaps we sometimes forget the older lessons. There have been some spectacular examples in recent years. Probably the Hubble Space Telescope ranks as the most visible example of very well-understood lessons of systems engineering being ignored. Those of us with a systems engineering background, indeed those of us without, would consider it essential when building a space telescope to bring all the many delicate parts together and test the whole thing out as one on the ground before launching it irretrievably into space. That pre-launch integration and test never happened. Most of us would consider that such a complex project should be managed by a single project office, to co-ordinate all the activities. It was not. We might imagine that the astronomers, for whom the telescope was being built after all, would have been continuously consulted—even, perhaps, in charge of the whole affair. They weren't.

This is not a cheap shot at NASA. The Hubble Telescope comes under my classification of a "noble venture", one that justifies itself because it transcends human pettiness in striving for greater things. But none of the things that went wrong was really technical; there were no real technical hang-ups. It was all human error. And that is a recurring theme; we seem to be so fascinated by the technology that we under-estimate the human dimension.

Engineer's Philosophy

This tendency to accentuate the technology culminates in the Engineer's Philosophy, a term coined by soft systems practitioners to deride the head-down, do-the-job, never-mind-the-consequences attitude they ascribe to engineers in general. Another view might suggest that, since industry sells ideas and technology, not people, surely its up to the customer to make sure that they know—and buy—what they want.

However...we are all aware of the "new whiz-bang" phenomenon: the system you bought isn't doing as well as you had hoped, but never mind, here comes the salesman with a new whiz-bang which will just do the trick nicely. But, of course, that is what happened last time. And, if you are not careful, it will happen again next time, too. You think it does not happen? It happens in spades—just think about company management information systems! Statistics regularly show that MISs fail to live up to expectations and are replaced at an alarming rate *and* without any clear relationship being established between MIS and corporate bottom line.

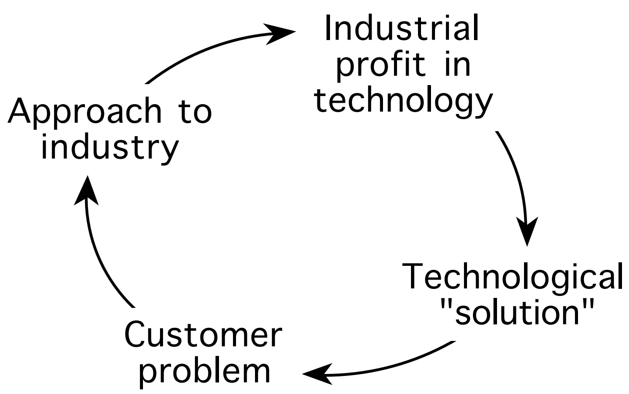

Figure 3. "The answer is 'more technology'—now, what was the question?" The diagram illustrates the natural tendency for industry to resolve a customer's problem by providing a technological solution—industry would make little or no profit without such an approach.

Customer and user are often effectively in the hands of industry in practice: they know their own environment, and their need, but sometimes have less understanding of how to satisfy that need. So, how can we get the right technology into C^2 systems when the customer depends on industry, but industry is (naturally) more concerned with selling technology than providing sound solutions to the customers real problem? See Figure 3. I was once asked, for example, by a customer to provide a computer-based tote display system to present squadron aircraft readiness states at an HQ. Instead, I suggested that the clerks could mark up readiness states with wax pencils on Plexiglas sheets, at a cost of $25 instead of $250,000. The customer was very happy. My company was very upset—until, that is, the customer approached us in connection with a much bigger contract because "we were so honest that they wished to do more business with us". We were lucky—I would not recommend it as a path to promotion!

Complexity and Outcome

Technology can lead us towards producing more complex solutions. Many people feel that complex solutions are necessary to address complex situations, but industry is not very good at dealing with complexity. Large project cost and time overruns are simply down to our difficulty in dealing with complexity. Consider the following quotations:—

> *"Systems which are complex, specialized and state of the art are high risk whether they be new tanks, the Channel Tunnel, command and control information systems or plain inventory management and control systems"*
>
> Brigadier W Bewley, Bicester—(UK MOD Depot)

> *"…due to a messianic faith in high technology",*
>
> *Management Today*, 91

The "messianic faith" may be responsible for our unshakeable belief that, somehow, we will "get it right next time!"

Adaptable Users, Rigid Systems

With our present technology and level of understanding, we are producing systems which are generally rigid if we compare them, for example, with biological systems, such as the humble mayfly. It may live for only a day, but its ability to fly, to seek food, to sense and follow the trail of a potential mate is beyond our wildest imaginings in terms of expert, intelligent or any other systems we might seek to build.

Humans are the planet's ultimate adapter, so far; we adapt so effectively that we are often unaware that we do so. Watch the operator of a mechanical digger manipulating a set of levers to excavate a ditch. Watch an AV8B/Harrier pilot as he/she hovers and dips the aircraft nose in salute to onlookers. Watch a stock market dealing room when there is a sudden price fluctuation. Watch a secretary faced with a new word processor package. Now look at the technology with which we support these people and you begin to see that the technology is doing several things:—

- Enabling particular tasks to be accomplished in a particular way—not necessarily the way in which the human would seek to operate
- Inhibiting the variety of tasks the human can undertake with this technological support
- Absorbing significant effort by the user to overcome the machine interface, rather than address the task which both human and machine face together

If the environment changes, humans adapt to the change while their machines remain appropriate only to the original situation: humans progressively desert the machines to interact with each other. Under stress, human operators set up their own interaction systems which dominate the behaviour and performance of the whole enterprise.

This phenomenon is causing concern in some quarters. Airline pilots are becoming progressively more dependent on aircraft automation, with electronic data displays, attitude and throttle controls, “autoland”, temperature controls, etc. So much so, that one airline has introduced training sessions to guard against complacency and over-confidence. Unless pilots have regular experience in handling the unexpected, they will not be able to cope when it arises. Flight simulators are not the complete answer: they are not real, the simulated defect is expected, the adrenaline does not flow so fast, and indeed there are even problems with simulators of inducing faults since there are so many safety devices which seek to prevent single defects causing full system failure. But, somehow, the unpredictable seems to happen in real life, even if it does not in rehearsal.

CHANGING ENVIRONMENTS

Dynamic change is about us, and never more so than in the world of command and control. A future war may be a dynamic patchwork, not a series of set pieces. Soldiers may become individual warriors, equipped with awesome firepower, and interconnected via elegant communications systems providing voice and graphic interchange. Each may be able to view another’s scene on demand. Each must, somehow, remain under overall control and act according to the commander’s intentions. Perhaps the individual warrior’s rôle is moving towards that of the individual policeman, towards the rôle of peacemaker/peacekeeper. The C^2 designer’s task may be to design a human-centred decision- support system for:—

- an unknown rôle, in…
- an unknown situation
- in an unknown area
- to address an unknown opponent, or…
- police an alien culture

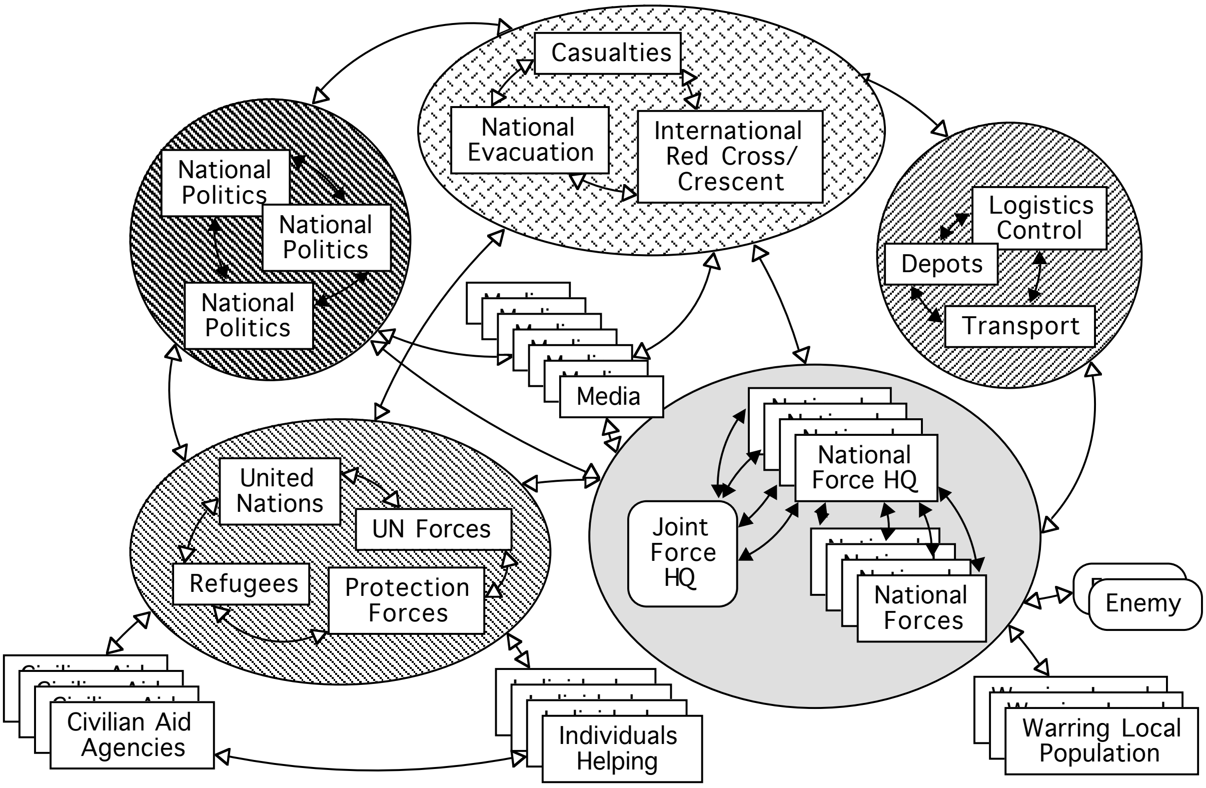

Figure 4. A more realistic view of Command and Control for the present and future? C^2 is a small part of a much larger, complex, interwoven set of systems, all interacting, competing, contradicting... The enemy is scarcely visible in this representation, but may be affecting all of the systems directly and/or indirectly. From this perspective, C^2 is seen as an open system, one amongst many, and the presently-dominant paradigm of linear, controlled behaviour is untenable.

For those system designers who feel that "the answer to the question is technology, now what is the question?" this presents a truly daunting challenge. It is not evident that much of the technology we build into today's C^2 systems is relevant to the future. Instead, consider how the morale of the individual warrior will be maintained, together with his *esprit de corps*. How about maintaining the individual soldier's belief in the justness of his cause, and in his need to remain impartial? And for those of us who still view the C^2 task as about making military decisions in war, see Figure 4, which might represent the situation, for example, in the former Yugoslavia—before NATO's involvement. Suppose, as is happening already in some quarters, command and control has to address the counter narcotics war? Suppose our forces become reassigned to the various anti-terrorist wars springing up with increasing frequency around the world? What then about our present technological solutions?

Chaotic Stability

Designers of command and control systems have a truly monumental task, dealing with requirements capture, software, hardware, and the legion of other aspects of design and development. Some concept of linear, or piece-wise linear systems behaviour tends to underlie the approaches that they take in the design processes. and yet, the real world with which their systems will have to cope is not linear. This is the world of the unknowable to which I referred earlier.

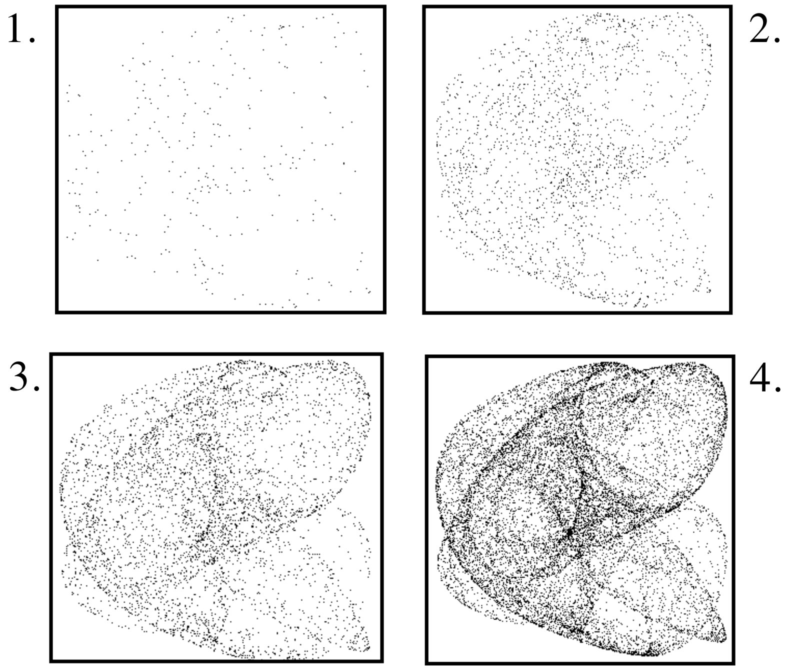

Figure 5. De Jong Chaos. The figure illustrates the growth of a chaotic situation. In diagram one, the eventual pattern has yet to form. Points arise seemingly randomly, and unpredictably. As the pattern forms, it can be seen as well-bounded, if complex. The figure arises from the interaction of two simple differential equations. How much more complex must be the relationship emerging between a number of people?

In the future world of the warrior, command and control will co-ordinate the activities of many soldiers at once instead of, as presently, of just a few formations. It will not be possible or sensible to control individual actions. Indeed, the situation may be similar to those faced by civilian police, where individuals or pairs of policemen on patrol may meet the unexpected at every turn. Police are trained to act on their initiative, to deal with situations as they arise. Perhaps the soldier of the future will need to be trained similarly, but he or she will face a more daunting task then the average policeman who is generally operating in an environment and culture with which they are familiar.

If we pursue this future environment further, we may see many soldiers operating semi-autonomously, each addressing different, unrelated situations. What of their command and control? The situation can be likened to a soccer match, where each of the players is an expert ballplayer in his own right. There is a captain, but he does not exercise immediate control. Instead, each player is schooled in the team strategy and has practised with the other players. They share a common goal and a common set of beliefs. The result is a well-oiled machine in which each of the players observes the game, takes advantages of openings, covers for colleagues without being told and fills in for casualties as a routine. To an observer, looking down on the game and observing, not the ball, but only the players, their movements would seem—and would *be*—chaotic. But their chaos would be bounded; it may be unpredictable on a minute by minute basis, but is consistent over time and is predictable in trend terms—see Figure 5.

The challenge for future command and control system designers, then, is to design systems with the flexibility and adaptability to cope with such chaotic, multi-faceted situations, maintaining force strategy, morale and self confidence without inhibiting team performance. This will not be simple. Consider Figure 6. At the left are three identical hard bodies, coupled together by some attractive force. The graph shows a computer simulation of their mutual behaviour. If the coupling is relatively slight, the three bodies behave simply and periodically, although not quite linearly. When the coupling is increased only slightly, the behaviour becomes chaotic. If this can occur for three simple, hard bodies, what might we expect from three complex soft bodies (people)—or several hundred?

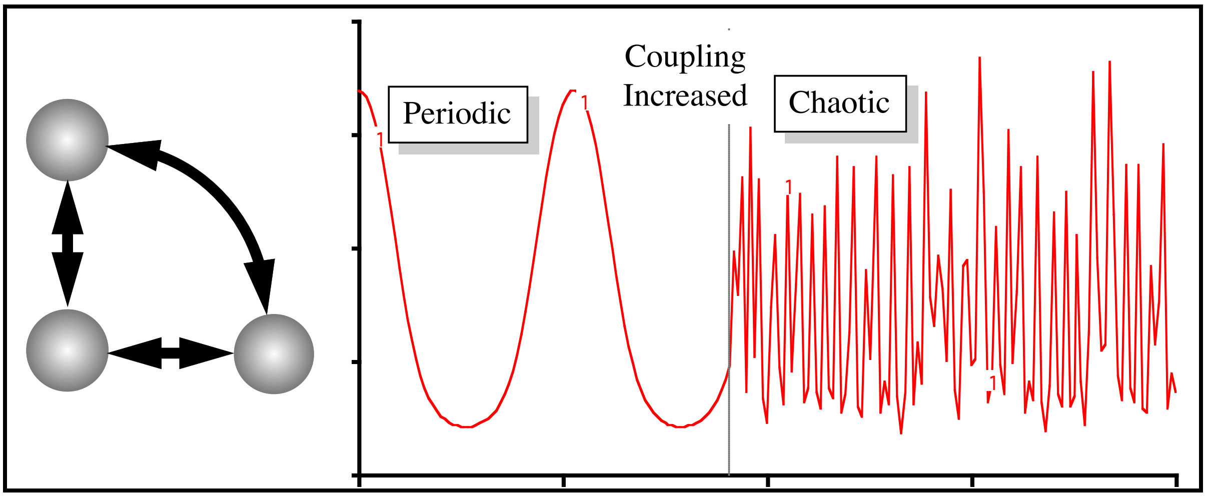

Figure 6. Three Body Behaviour. Three bodies move under mutual attraction, at left. According to the degree of their mutual inter-coupling, their behaviour may be periodic or chaotic, at right. If three simple hard bodies can behave in this fashion, how might three complex soft bodies (people) behave?

Human Factors versus Classic Engineering

How can we develop better systems? One thing is certain—the user and his environment must be taken into account in design, to an even greater degree than at present. Some parts of industry are, to their credit, showing the way. But it is no exaggeration to say that human factors engineers are the poor relations in many engineering companies—and some companies have no such expertise.

When designing an information system for users, you might expect the humans to be at the centre of the design process—after all, they ultimately both supply and receive/use the information. I can almost guarantee that an MIS design will show either the processors or the internal communications at the centre, not the humans. And that reveals a state of mind.

Are human factors engineers "in" at the beginning of the design, then? Generally not. Quite often they are brought in as an after-thought: of course, it is rather difficult to "add-in" human factors once the technology has been set in concrete. And human factors are often confined to Human-Computer Interface (HCI) to determine the colours and symbols to use to make a display easy to read. These are not unimportant issues, but they hardly constitute HCI and HCI in its turn is only a small part of the interface between humans and their environment. I worked recently with a group of building design engineers recently who did not want an architect to be part of the group in case he or she introduced "irrelevancies", such as feel, spaciousness, perspective, convenience, etc., into the discussions at too early a stage!

POTENTIAL PARADIGMS FOR PEAK PERFORMANCE (P^4)

There are many different paradigms which might better suit the world in which we begin to find ourselves. Here are a few.

User Architects

Like it or not, written specifications for command and control systems are a poor medium for conveying requirements. Written language cannot convey the wealth of meaning and intent, the background culture, the ingrained procedures, the understanding of the requirement. Sit-in on a knowledge elicitation session, for instance, between a young engineer and a serving officer with 25 years' experience. The young engineer cannot comprehend the implications of the responses to questions. The experienced officer is truly unaware of the extent of his specialized knowledge—it has become second nature to him.

There could be a better way. Suppose engineers were able to create an immersion virtual environment, i.e. one in which several experience, co-operating operators could be immersed together, wearing 3-D helmets, etc. Suppose further that this environment could be manipulated by the operators. They could:

- lay out furniture
- select equipment
- organize themselves
- respond to external threats fed to them periodically
- adjust the virtual equipment and systems to gradually improve their group performance against a variety of threats, increasing/reducing the size of the team, calling up/dispensing with systems as their developing capability demanded

If several such teams existed, they could mutually develop each others' performance by competing and co-operating as mutual enemies and allies. Now this bears some thinking about. At present, our approach to HCI tends to concentrate on a human and a computer. In a multi-person synthetic environment, it would be possible to improve, and specify the requirements for, the whole team at once—something we presently have no way of doing. Moreover, we rarely develop complete team performance under pressure, although we know it to be important.

Immersion synthetic environments would enable engineers to concentrate on creating really effective virtual environments, while experienced operators effectively developed their own requirements under representative combat conditions. I call this the User-Architect paradigm. Experienced users effectively specify their requirements in the conditions they impose on the virtual environment: no written specification to be misinterpreted; no need to transfer years of experience; team development into the bargain.

Of course there are problems. Technology does not give us adequate synthetic environments at present, and "simulator sickness" is common in those we have. But surely those are the challenges to be resolved, not engineers trying to act as surrogate operators.

It does not end there. Why could operators not create their own, personalized virtual interface? A pilot would climb into a cockpit of an aircraft with which he might be less than familiar, plug in his personal connector and, as he does so, the controls and displays configure to his preferences. So, his experience and training, culminating in instinctive reactions through panel and display layouts, would last much longer.

The Next Generation

You don't watch Startrek—the Next Generation? How do you hope to keep up with the technology? Sometimes the writers of science fiction, perhaps unfettered by too much experience, come up with interesting ideas. Two on the Next Generation are particularly interesting: the universal interface and instantaneous call routing

The universal interface seems like magic to an engineer. The crew of the Enterprise seem able to connect anything to anything with consummate ease. Computers to communications. Power supplies to conduits. Optical systems to voice translators. You name it, they connect it. How different from our perennial problems with interoperability!

How would you design the universal interface? Suppose a system, *A*, wished to communicate with another system, *B*. *A* interrogates *B*. *B* publishes (transmits) details of its input interface details back to *A*. *A* is equipped with an automatic patch panel, which makes all the connections required by *B*. *A* then connects to *B*. Communication from *B* to *A* requires that *B* also have an automatic patch panel, so the two ends become symmetrical. Easy isn't it? Well, clearly it is not. But think of the advantages to C^3 systems in future multinational force organizations. The one problem that really bugs is the intercommunication problem, with different protocols, message standards, catalogues—the list is endless. We could fix it if we had a mind to... Once we get the technology problems out the way, we can then get down to the real problems of inter-operation between different people, different cultures, different practices, etc.

Instantaneous route calling on the Next Generation seemed tricky at first. You know the scene. The captain on the bridge talks to Number One over a radio link, simply by raising his voice. Number One replies from the windswept surface of some alien planet. Nobody else hears. No routing, no headers, no creating a link first. How could we do that?

With cell telephone networks and CNI systems like JTIDS, the position and identity of subscribers is known within the system. When the captain says “Number One”, voice recognition interprets the words as an address, temporarily storing any preceding words, and routes the voice message complete to the appropriate receiver. Number One, and all other cell members, carries a beacon (in the Starfleet badge) which is a prerequisite for the system to operate. In fact, it would not be difficult to set up such a communication system with current technology. So, why don’t we? With the advent of the individual warrior, and with greater demands being placed upon our police forces, such concepts may indeed emerge. If the many warriors are to keep in close touch with each other, how much simpler to speak to each other by name or rôle, and let the system look after the rest.

CONCLUSION

It is a compelling thought that a system changes the environment into which it is introduced. This means, of course, that it is simply not possible to sit down and specify a system, since knowledge of the change which the system will engender would be needed, but is generally neither known nor knowable. Current obsession with fixed price, design/construct and similar contracting philosophies may not be questioned, but are highly questionable nonetheless, for this very reason.

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