

# Integrating Mechatronics in Manufacturing and Related Engineering Curricula\*

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*Typical prototypes of manufacturing and related engineering programs are briefly reviewed. For the professionally aligned readers, arguments are presented in favour of orienting the electronics and controls courses towards automation by integrating them all to form a core of the mechatronics program stream. These courses would thus take an obviously common direction, allowing the manufacturing engineers to function better as technology integrators at the machine, workcentre or shopfloor levels of modern manufacturing organisations. This objective is difficult to realise when the electronics, controls and automation subjects are taught in isolation one from another. Paradoxically, it matters little whether the automation course is taught before or after the other two. Critical topics linking all three are usually missing. With different teaching departments involved, the lack of emphasis on the commonality of purpose is near total. Thus, with only disconnected stepping-stones made available, the graduates' ability for professional self-improvement through life-long learning is hampered.*

## INTRODUCTION

BOTH AS A PROFESSION and as an engineering discipline, manufacturing engineering is growing rapidly in its breadth and scope. For instance, the rapid progress in computer-related technologies has 'triggered an unprecedented metamorphosis and globalisation of manufacturing during the last half of the [last] century' [1]. These developments have 'started to awaken us to the fact that, in actuality, manufacturing is not just a collection of various types of activities and processes but instead a system' [2].

In the past, it had sufficed for most manufacturing engineers to be 'technical specialists' functioning at the machine, workcentre, and/or shopfloor levels (see Fig. 1). These levels have now become increasingly mechatronic in nature as much of the functionality of the conventional systems has been transferred from mechanical to the electronics and software domains. Furthermore, modern-day manufacturing engineers are also expected to work as 'operations integrators' at the factory level and/or, even, 'manufacturing strategists' working at the enterprise or extended enterprise levels [3].

Inevitably, the expanding disciplinary scope is subjecting manufacturing engineering education to 'tensions' arising from the requirement to introduce 'new topics, for example, logistics, legal aspects, financial, personnel and human factors . . . This need is in conflict with the diverse requirements for, *inter alia*, basic science and technology, design, environmental awareness, practical training *et cetera*' [4].

Often, while designing undergraduate manufacturing engineering programs, the tensions are exacerbated by societal limitations on program duration (usually, three or four years). Almost without exception, each curriculum development team is forced to be selective in its choice of topics. Thus, there is no single universally accepted prototype of undergraduate manufacturing engineering education. However, since *variety is the spice of life*, this should not be construed as an indictment of manufacturing education worldwide. Given the inherently dynamic nature of manufacturing engineering, it might be better to let manufacturing engineering education evolve in a Darwinian fashion—'incremental evolution', 'mutation', 'survival of the fittest'—and the rest. However, the last notion requires that the evolution steps are periodically communicated and assessed with a view to positively influencing curricular evolutionary steps elsewhere.

This paper outlines a selection of prototypes of undergraduate manufacturing engineering programs and discusses the implications with regard to how one should design and implement curricular components related to controls, electronics and automation.

## PROTOTYPES OF UNDERGRADUATE MANUFACTURING ENGINEERING PROGRAMS

Figure 2 lists a selection of prototypes of undergraduate manufacturing engineering programs. One classical prototype is 'science-based'. This prototype recognises that the purpose of undergraduate education is to support the long-term

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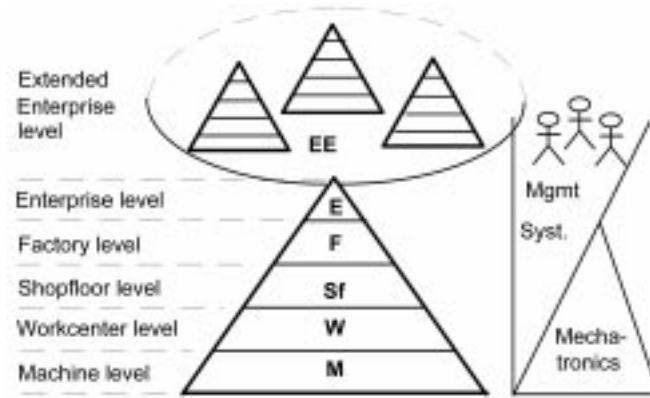


Fig. 1. Modern manufacturing organisation.

careers (often spanning around forty years) of students. Hence, the emphasis is on scientific principles that have much longer life cycles than those of technologies and products. With this prototype, typically, courses focusing on basic sciences of particular interest to manufacturing engineers (e.g., materials science, solid mechanics, electronics, and control systems) are taught in the earlier years of the program. This is followed by a set of courses directed at a scientific understanding of manufacturing processes, and shopfloor level manufacturing planning and control so as to underpin courses focusing on manufacturing applications and problem solving in later years. This prototype is particularly successful when the student population as a whole is intellectually inclined and proficient.

Another classical prototype is the professionally oriented one that places premium on the utility of the student soon after graduation to industry. Typically, this prototype trades some of the emphasis on scientific principles in favour of increased skills of application and integration. The prototype is often preferred in regions (e.g., the U.K. and Hong Kong) where, historically, engineering programs have striven to attain accreditation from local and/or international professional institutions. Less intellectually endowed students seem to thrive on such professionally oriented programs.

Classical professionally oriented programs focus on technological issues of importance in performing manufacturing engineering functions at the workcentre and shopfloor levels (and, to some

extent, at the machine level)—see Fig. 3. Initially, most professionally oriented programs ‘stayed in the middle’ around the shopfloor level issues (Sf) with some upward integration of factory level issues (F) and some downward integration of workcentre level (W) issues. However, the programs started diverging as pressures for broadening curricula mounted. Some followed the path of upward integration by progressively integrating issues of interest at higher levels (enterprise and extended enterprise levels). Such programs acquired a ‘managerial’ flavour. Others chose a downward integrative path focusing on technological issues at the workcentre and machine levels (W and M). Some were initially ambivalent and, hence, chose the ‘comprehensively integrated’ path.

All the prototypes described above are valid. The choice depends upon the local priorities and conditions. For instance, when it had started first in 1988/89, the B.Eng. (Honours) in Manufacturing Engineering program at City University of Hong Kong had adopted the comprehensively integrated path because the majority of manufacturing enterprises were operating locally [5]. The need of the day was for graduates that were capable of promoting the use of computers at the shop floor level but with a broad understanding of technological issues at the work-centre and machine levels (downward integration) as well as managerial issues at the enterprise level (upward integration). However, we soon realised that such an extensive integration could not be effectively



Fig. 2. Prototypes of manufacturing programs.

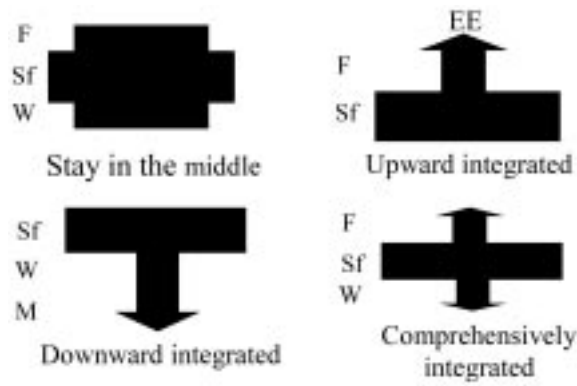


Fig. 3. Professionally oriented prototypes.

implemented within the program span of three years. Further, meanwhile, Hong Kong's manufacturing sector had undergone a phenomenal structural change. Following the opening up of mainland China, over 80% of Hong Kong's manufacturing shops were moved into the mainland while retaining product and plant design, financing, marketing, financing, strategic management, etc., within Hong Kong. In response to the changed employer expectations, our program was split into three streams:

- Systems stream (S): upward integrated;
- Manufacturing technology stream (M): stay in the middle;
- Electronic/computer automated stream (E): downward integrated.

Inevitably, these changes in our curricular structure prompted us to apply different pedagogic approaches to different streams of students.

Since we had already been operating a separate undergraduate program in Mechatronic Engineering [6], our downward integrated E-stream soon acquired a distinctly mechatronic flavour. (Mechatronic Engineering may be defined as 'a synergistic combination of precision mechanical engineering, electronic control and systems thinking in the design of products and manufacturing processes [7].' Thus, the course group related to controls, electronics and automation forms an important part of this stream's curriculum. The rest of this paper will discuss some pedagogic approaches particularly suited while addressing this subject group in a professionally oriented program that is not 'upward integrated'.

### THE PROBLEM

Manufacturing engineers often conceptualise various end-attachments suitable for particular tasks they encounter. Attaching them to robots is not always feasible either in terms of the cost, prohibitive weight of the attachment, or range required. Hence, it is usually necessary to design corresponding motion systems and complete the rest of machines such as that illustrated in Fig. 4 ('the Task'). Manufacturing engineers receive university training in the individual disciplines relevant to this Task (including electronics,

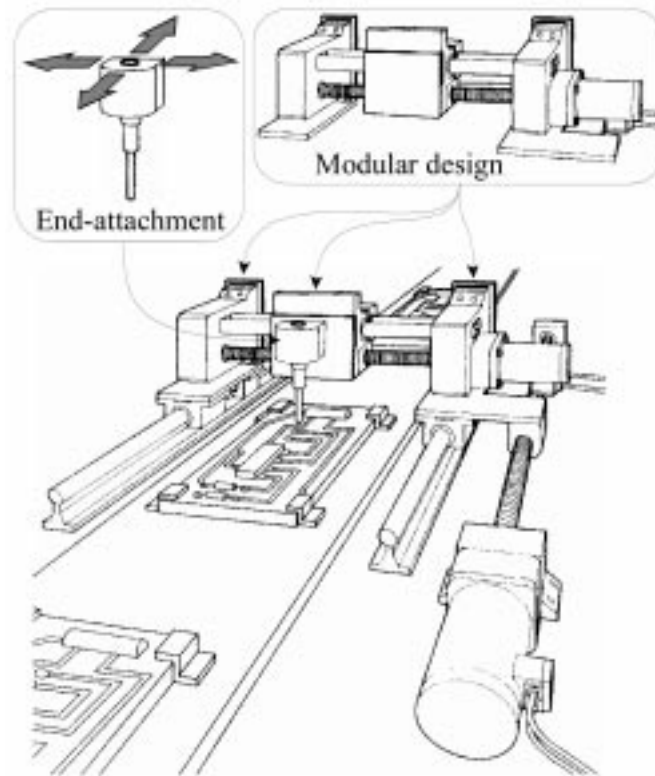


Fig. 4. Assembly machine.

mechanics, controls, programming, automation, and design).

In the authors' experience, however, for the most part, manufacturing engineering graduates try to avoid having to face the not-so-tough challenges associated with the said Task. While this Task might appear complex because the end-attachment must reach any point in the given plane with high accuracy, it is accomplished easily through integration of commercially available modules. Complete with a motor, brake, lead-screw, slides, and sensors, a module like this (insert of Fig. 4), provides support, actuation, and position and velocity feedback for the load (end-attachment) along the cross-wise direction in Fig. 4. It can be purchased pre-assembled, of custom length and from a range of capacities. Combining two or three of these to achieve motion in a given plane or space is a simple task indeed. Controlling such motion is also simple with commercially available motion-controllers. These controllers come with software dedicated for controlling motion along multiple degrees of freedom. They auto-tune themselves for the optimum performance along each axis with respect to the design requirements, can correct for many mechanical problems such as the lack of orthogonality between pairs of axes, static deflections, transmission backlash, etc. Some electronic interfacing is also needed to complete the overall system. This is often needed even if all machines are to be purchased ready-made rather than built in-house (functioning at the shopfloor level).

Even with the end-attachment in hand, manufacturing engineers' predominant inability to complete the relatively simple Task of Fig. 4 autonomously (without cooperation of engineers from other disciplines) may translate into a mindset that is less receptive to the introduction of automation—in order to avoid unfamiliar tasks. The consequences of this mindset affect the entire society, as the alternative to automation is often a move of the manufacturing facility to a jurisdiction with less expensive labour force.

### CONTRADICTION?

While methods for equipment control used in manufacturing have changed immensely over the last three decades, manufacturing education in this domain has not kept up with the developments. Changes in the syllabus for the controls course, for example, largely reflect the advancement of the discipline itself (such as the introduction of the state-space system description some time ago) or the improvement of the user-friendliness in doing the same old things more conveniently with the aid of computerised packages (such as plotting the root-locus using MATLAB<sup>®</sup> software). Details of the control theory (Routh's stability criterion, Cauchy's theorem and root-locus come to mind) are often taught under the 'pretence' of providing

deep knowledge in the domain of controls, this domain being the stepping-stone to unmanned operations. However, the course on automation as it stands at present could precede the one on controls without loss of continuity. It could similarly precede the electronics course that is often dominated by material that has had a diminished significance already for some 20 odd years. The connection between the electronics, controls and automation courses is usually not made obvious to the students and their integration and complementarity are incomplete at best.

### TO INCLUDE OR NOT TO INCLUDE

The theoretical details from the domain of controls do not generally represent the deep domain knowledge needed to complete the design of the device shown in Fig. 4. Insistence on those details has a negative effect as it detracts from the key controls concepts and students often pass the controls course without true intuitive understanding and cause-effect visualisation of terms such as the derivative control, integral control, or bandwidth; terms that must be understood well in order to make full use of motion controllers. To clarify this point by analogy, while a deep intuitive understanding and visualisation of stresses is required to properly execute a finite element method (FEM) of stress analysis, one does not have to know the analytic solution of stresses in a curved plate with holes as that is precisely what FEM will calculate if applied properly—which reinforces the need for deep understanding of the basics.

Even if the fresh manufacturing engineering graduate successfully applies say the root-locus technique, what purpose does this accomplish? (S)he cannot complete the assembly machine because (s)he fears even to look at all the electronic interconnections such as the PWM (pulse width modulation), PFM (pulse frequency modulation) or analogue inputs of the servo amplifier. Not to mention that (s)he could not carry out the root-locus technique precisely because (s)he does not know how to connect the system and therefore does not have the transfer function. The knowledge required to overcome this vicious circle is relatively simple, quite interesting (students would enjoy this material infinitely more than the root-locus technique) and it could be shared between modified electronics, controls and automation courses. The situation would then be avoided where a manufacturing engineering graduate, with a general purpose controller (rather than motion controller) at her/his disposal, does not even know where to start, let alone attempt to write a simple control program that includes the derivative and integral actions for driving a load along a linear slide.

In the authors' opinion, the worst consequence of unadjusted syllabi is the confusion created in the mind of a fresh manufacturing engineering

graduate. Faced with an equipment design task, (s)he is likely to check her/his university notes. (S)he will quickly realise the need for a mathematical model of the system whether (s)he chooses Routh's or Nyquist stability criterion. However, probably very few practising manufacturing engineers have ever written a mathematical model of a system under their responsibility and then calculated, as trained at the university, the required controller parameters that assure the desired performance. To begin with, in the case of some pick and place mechanism, for example,

- real-world motion systems commonly include non-linear influences (amplifier saturation, friction, hysteresis, stiction . . .)
- multiple axes have to be controlled, each with respect to a number of variables (position, velocity, acceleration . . .) simultaneously, in the presence of strong cross-coupling between at least some of these, and
- the moment of inertia reflected onto the motor shaft varies with the load position, meaning that the system is not one with constant parameters.

All these aspects are prohibitive for the direct application of the theory of *linear control of single-input-single-output systems with constant parameters* that manufacturing engineers were trained for at the university and that the root-locus technique is valid for.

### MECHATRONICS IN MANUFACTURING ENGINEERING SYLLABI

In the authors' experience, insisting on details of the linear control theory for simple systems has an added disadvantage that the students' intuitive understanding of the most fundamental concepts is clouded to the point that disappointingly few alumni can recall almost any. A preferred alternative for manufacturing engineering students may be to insist that deep understanding of only the basic PID control fundamentals is gained. Then, introduce the more intuitive concepts such as fuzzy control, without going into the mathematical foundation of fuzzy logic. Both have to be computer-implemented fully with the actual programming code analysed in order to open the door for further explorations upon graduation, and with all electrical connections in place.

By using commercially available motion controllers in the automation course the students will quickly realise that they have been empowered to solve virtually any automation task. They may focus fully on the task itself, rather than on how to control motors to achieve that task, the latter now being delegated to the routines embedded in the controller. A discussion here about auto-tuning of the controller parameters (P, I, D . . .) would reinforce the notion that the pieces of the curriculum actually fit together. Interfacing still remains a problem (typically of the encoder and

servo-amplifier) and should perhaps be the prime focus of the electronics course specifically designed for manufacturing engineering students.

Much of the circuit theory and almost everything about transistors (except in switching circuits) that has been entrenched in the electronics syllabi for many years would have to be replaced by the black-box approach to the common integrated circuits (operational amplifiers, logic gates, servo controllers with PWM/PFM outputs . . .). This high level approach would be supplemented by details on selected topics such as switch de-bouncing, impedance matching, voltage level conversion and similar interfacing problems. Such details are not easy to master on one's own and, if not addressed in the classroom, are likely to become an impenetrable barrier to a manufacturing engineer's hands-on, life-long learning endeavour in technology integration.

Overall, the traditional boundaries between electronics, controls and automation subjects should become blurred, with the emphasis shifting from mechanics towards electronics and computing to reflect the historical transfer of automation functions from mechanical to electronics and software domains as evident by the phasing out of the Geneva mechanism used to generate indexing motion of the turntables. The result would be a more mechatronic flavoured content of most engineering courses including those on design. However, the majority of teaching staff in manufacturing engineering departments probably feel rather uncomfortable with electronics. Hence, instead of intertwining electronics into core engineering subjects, it is often considered easier to send the students to the electronics department for an additional course or two on basic electronics. The students would get there much detail about the material they may not be in position to apply upon graduation, but will still not know how to complete the design of Fig. 4.

The integration of the electronics, controls and automation courses into three mechatronics counterparts would assure that the problem of drain characteristics of field effect transistors being available with insufficient precision for their graphical performance-analysis with small signal amplitudes, gets a low priority level when deciding what to include in the manufacturing engineers' curriculum—similarly for the root-locus technique from the controls domain. After all, much of manufacturing engineering is about integration, and assuring that the syllabi are well integrated with a specific aim in mind should therefore not be too much to expect from professors of manufacturing engineering.

### CONCLUSION

Major prototypes of undergraduate manufacturing engineering programs are science based and professionally oriented ones. The varieties of

the professionally oriented program include the 'upward integrated', 'downward integrated', 'comprehensively integrated' and 'stay in the middle' prototypes. For the latter three, the downward integrated in particular, the need to give to the controls and electronics subjects a better sense of purpose and direction is suggested. It is recognised that these courses make manufacturing engineering students familiar with the present-day all-important technical concepts of system transient response, phase shift, bandwidth and frequency-dependent performance. It is suggested, however, that the benefits the graduates derive from this group of long-established courses could be far greater than is commonly the case if the

respective syllabi would be better integrated with a clear convergence towards the automation course. As it stands at present, the order in which these three courses are taught is irrelevant. Crucial links between them are largely missing. For the electronics and controls subjects, the sense of purpose and direction in the curriculum are not made sufficiently clear to the students and the true mechatronic character is absent. As a result, the manufacturing engineering graduates' ability for self-improvement in the domain of technology integration is hindered, and so is their chance for career progression towards the enterprise level of the manufacturing organisation for which they received substantial university training.

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