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DOI : 10.1109/IROS.1992.594535
DO I NEED A ROBOT OR A NONROBOT AUTOMATED SYSTEM?

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Abstract - In manufacturing automation, the current focus is on integration at enterprise level. This however has not reduced the need for automation on the shopfloor. On the contrary, the latter has become more pressing. On the shopfloor, major manufacturing costs are related to handling and assembly operations. Difficulties in automating those operations are twofold. First, there is usually a line beyond which manual operation remains the most economical solution today. And then for each application, the proper level of sophistication in terms of automation technology should be adopted. The paper concentrates on the second difficulty. Most often, products and processes can be designed so as to require fairly simple automated systems for their manufacturing (on/off devices, programmable logic controllers, independent actuators, etc.). But when the application features significant position and/or orientation uncertainties (mathematical space of dimension 3 or more), some kind of perception is required to cope with them, and this usually results in adaptive workpiece or tool trajectories. Robotics provide unmatched solutions for such multi-dimensional, coordinated motions. General guidelines are introduced in order to select the appropriate type of component for automation. Then, two case studies follow. In both cases, the application is complex, in terms of parameter variability. Many examples are given of correspondence between given guidelines and concrete, low-level details. In particular, while in the first case automated solutions can be devised with traditional, multiple independent servoed motions and general-purpose computers, in the second one, industrial robotics with dedicated controllers provide the right answer.

I. INTRODUCTION

Integration (CIM: computer integrated manufacturing) is now a major trend in industrial organization. To achieve such a goal, enterprises must define a coherent concept for many areas yet too often isolated: design, quality control, production planning and scheduling, etc. But in each of them, technical excellence and further automation are still required. The scope of the paper is not the complete CIM problem, but is limited to one of its most challenging components: manufacturing on the shopfloor. The challenge comes here from the fact that to be controlled by computer means, virtually all processes must be automated. This is difficult because production is very heterogeneous. While some pieces of equipment can be controlled remotely (e.g. NC machines, robots), most traditional processes have little flexibility or even no communication capabilities at all (e.g. manual or purely mechanical operations).

In economical terms, industrial robotics and automation have led sometimes to unsurpassed successes but they have also occasionally been the evident cause of failures. The key reasons behind such uneven performances are not the same for both fields.

In the case of general automation, problems have mostly come from a bad tradeoff in task division or role assignments for machines and human operators. In the case of robotics, even though this reason sometimes applies also, it is more the lack of understanding of the specific strengths of robotic technology versus other automation approaches which has proved critical.

The paper attempts to assess where a robot is appropriate, and where other automation technologies are preferable. Advances are numerous in very specialized technical areas. It is not the aim of this paper to discuss such topics. Instead, a rather broad perspective is adopted (generalist's point of view), which is believed to be of significant practical value. First we get back to essentials and then proceed to concrete case studies. Part 2 theoretically delineates what is common to robotics and automation and what is specific to each of them. The following section (§ 3) describes two projects currently under way, and provides examples on how the general ideas can be applied in concrete terms.

II. ROBOTICS AND AUTOMATION

Robotics and automation have a lot in common, which is briefly discussed first. The following paragraphs will describe their singularities.

A. Commonalities

In one extreme sense, robotics could be viewed as a simple component of automation. On the opposite the perception is,

In CIM terminology, automation on the shopfloor is sometimes referred to as CAM (computer aided manufacturing). But most often CAM has a much more narrow meaning, and simply describes the capability to postprocess CAD data and to download them as numeric programs for machine-tools. In practice, the meaning of CAD (Computer aided design) has also shrunk and now tends to equate "design" with "geometrical modeling of mechanical structures".

0-7803-0737-2/92$03.00 1992©IEEE 1161
sometimes, that robotics is a kind of synonym for advanced automation. Even though such extreme views are clearly excessive, it is nevertheless true that both fields widely overlap.

Topics common to both fields are numerous: vision and sensor-based perception, low-level control (such as axis servoing), modeling, factory level communications (CIM context), etc.. In practice some entire projects can rightly be given either the automation label or the robotics one [e.g. 1].

Let's see in more details how the two fields differ.

B. What is automation

Essential for automation is the basic control block of Fig.1. In this classical case, measurements typically consist in scalar values. But in practice, the complexity of measurement/observation feedback path may widely vary: modern industrial workshops are tightly structured, which most often allows to keep the feedback signal as simple as a boolean value (e.g. [2]) or even to suppress it. But it also happens, at the other extreme, that automatic loops convey signals with high semantic content. High semantic content refers to cases when measurement is not a simple scalar, such as temperature or voltage values, but consists in more abstract information, such as for example visual recognition of industrial workpieces, or complex process monitoring.

Automation is a discipline which tends to introduce, in systems otherwise controlled by humans, many basic control blocks, or loops with higher semantic contents.

![Fig.1 Basic control loop](image)

It can be traced back to last century when the first mechanical regulators for steam machines were invented. Progressively, it developed with the advent of electricity, relays, computers and, in recent years, microelectronics.

In industrial automation, trend is towards higher complexity in number of interrelated loops, and increased abstraction in information flows. In particular, there is now a new research focus on Intelligent Manufacturing Systems (IMS), which addresses the same theme. Notice that while the word intelligence has many conflicting meanings in common English (information, knowledge, expertise, ability to learn...), formal definitions and metrics for it have been proposed in cognitive sciences (in particular in [3], intelligence is part of the theory as a derivative, with respect to experience data, of expertise, i.e. knowledge and processing speed product).

In one of the latest phases, the progress in automation brought about the robots. But with the advent of robots, the word of automation took a new twist. People have come to oppose robotic solutions to other ones, often said to be "hard", or "traditional" automation. Actually, this latter type of automation is not necessarily hard nor frozen in old habits. It is often flexible and undergoes its own evolution. As a matter of fact, it is just "non-robotic" automation (NRA).

NRA systems are now prevalent in industrial workshops, where they are useful for numerous particular, process-oriented operations, as well as for many applications in general handling or assembly. This latter fields have been characterized by an impressive amount of know-how in practice, which contrasts with their shallow theoretical foundations (as a good example of research attempting to bridge the gap, refer to [4], or [5] and references in it). On the shopfloor the problem is usually more to devise and manage simple but numerous control blocks (e.g. [6]) than to design and implement a few sophisticated regulators (e.g. [7]).

To circumscribe more clearly the grounds of automation in its restricted sense (i.e. NRA), it is appropriate to define accurately what robotics can do.

Robotics has grown out of general automation because of its original properties, and its specific impact on many handling, process manufacturing, and assembly operations. It is discussed more thoroughly below.

C. Specifics of robots

Consider the difference between the feedback loop of general automation (Fig.1) and a schematic representation of the robot (Fig.2). Measurement/observation generalizes to perception, control to decision-making, and action on the driven system becomes here primarily mechanical. In addition, a dedicated role is assigned to locomotion.

![Fig.2 Schematic representation of a robot](image)

Notice that industrial robots (I.R.) are different from robots considered in other technical or scientific fields. In exploration, the perception and locomotion faculties are boosted. Researchers in artificial intelligence tend to pay a primary interest in decision aspects.
Industrial robots have a major focus on mechanical action. Perception and decision-making are often liminal, and locomotion quasi-nonexistent yet. As a matter of fact, still a few years ago, mobile robots were excluded from major symposia on industrial robots.

The essential contribution of robotics to the workshop is a unique capability to move objects (workpieces or tools) along freely programmable trajectories. This task, which is very natural in humans, implies to coordinate multiple axes of motion, and leads to serious scientific and technical problems, far beyond what the layman expects.

Axis coordination can be met in some other systems, such as the milling machines (textile, paper, metal-sheet industry), but here the problem is extremely simple in comparison: the coordinate space is typically of dimension 1, versus typical dimensions of order 3 to 6 (free position and orientation of a solid) in the case of robots!

In industrial robots, kinematic aspects are multiple. Most often, the problem is to control an arm, which consists in a chain of sequential joints. But sometimes, flexible motion of objects is achieved by the concurrent use of parallel joints. In addition, a serious challenge is encountered when hand control is considered (it is well known that the human hand has about 20 degrees of freedom, versus only 7 for the arm...). Multi-fingered, sensor-equipped, or "dumb", the end-effector plays a very special role in industrial robots. No standard solution exists and its proper, application-oriented design, is often critical for total system economic viability.

It becomes now clear that a robot must be specifically used when the application requires objects or tools to be moved along complex paths. Examples of such industrial applications can be found in many manufacturing processes (arc and point welding, deburring, polishing, glueing, painting, etc.). In addition, robots are also necessary for more general tasks such as complex (i.e. multi-axis) handling and assembly. This latter case often arises in the production of individual products. But it is even more frequent in flexible production, i.e. when batch manufacturing is considered. Here good performances in terms of short changeover time are usually of major importance.

Research topics in industrial robotics are typically geared towards cycle time improvement or increased flexibility; models for dynamic control (e.g. [8]); faster mechanical architectures (e.g. [9]); multiple arm coordination (e.g. [10]); faster processor architectures for multi-axis control; perception-based path definition and control (e.g. [11], [12]); trajectory planning with collision avoidance; articulated grippers (e.g. Utah hand); etc.

Various aspects of automation have been presented above: trend to structure manufacturing tasks ("design for automation"), use of simple control blocks, coping with position uncertainties with sensors and adaptive motions, need of robots for specific operations, etc. This leads naturally to guidelines, which are given at the end of the paper: Appendix A provides a summary of key application particulars, along with automation components (robotic or other ones) usually proven appropriate.

III. Case Studies

The preceding section has discussed the respective merits of two complementary types of industrial automation. Here we confront general considerations to concrete situations. Examples are taken from two research projects in which the Laboratory of Robotics and Automation (LRA) of EINEV is but one partner (re. §Acknowledgements). The first one is supported by public funding and industrial partners at the European level. The second one is part of a Swiss National Research Program.

A. CIFAS Project

CIFAS is a large research project which is developed jointly by industrial partners and research/educational Institutes ([13]). After a general overview of the project, attention will be restricted onto a few key aspects relating to §2 discussions.

1) Project overview: CIFAS is an acronym for Computer Integrated Flexible Assembly System. The goal is to suggest a global reorganization of a century-old factory, taking advantage of the most appropriate current CIM technologies.

![A typical product to manufacture in CIFAS](image-url)
solutions have been developed such as for example a Computer Aided Musical Arrangement system (CAMA), or specialized CNC machines for musical manufacturing and harmonic tuning.

A typical product is shown in Fig.3. This is a music box where three main components can be readily identified: a keyboard, which is the sound generating element; the excitation cylinder, which carries a number of pins, each activating a particular note of the keyboard; and finally the remaining supplies (base, spring box, speed regulator, etc.).

A general view of the process under consideration is shown in Fig.4. Schematically, three main material flows converge to a final assembly line: The first one corresponds to cylinder manufacturing (hole drilling, pin insertion, etc.). The keyboard is progressively manufactured in another flow (cutting, thermal treatment, multi-step frequency tuning, etc.). The last flow line relates to supplies and ancillary workpiece production (metal-sheet forming, frame machining or injection, spring loading, preassembly, etc.). Of particular interest is the final assembly, which will be discussed below in more details. While Fig.4 displays material flows in solid lines, information flows are also made visible by data networks and dashed arrows.

Notice that the above description is minimal. It is sufficient for our purpose but in fact the number of elementary operations and corresponding know-how are impressive.

Areas where further automation is of primary interest have been identified to be the following: material transfer between machine-tools; assembly process, in various phases and in particular for final tuning; tighter manufacturing tolerances in order to simplify manufacturing process as well as to increase final product quality. Moreover, improvements are expected in related product and process design.

2) Particular aspects: The most interesting operation to analyze is probably final assembly. This step in the process is challenging, because all manufacturing tolerances accumulate and here must be compensated for, in order to guarantee proper product functioning and quality standards. The problem requires integration of various technologies. The use of a robot in this application is debatable, but found below not to be necessary.

Position uncertainties. Variations in final cylinder position, with respect to the base are of dimension 5! Uncertain lateral and vertical shifts stem from loose tolerances on spring box stamping; for frontal positioning, an additional change may be due to the actual size of trimmed pins; there are two additional degrees of uncertainty, corresponding to slight misalignment errors. A careful analysis shows however that a satisfactory result can be achieved by appropriate adaptive 3-dimensional positioning of keyboard in a horizontal plane.

Task inherently complex. In view of the problem dimensionality, the task can be considered complex. Therefore, some level of sophistication in the solution should be expected.

Design changes. Some changes in current design could help solve the problem. In particular, appropriate vertical stops in the keyboard bed can guarantee an horizontal keyboard position, thereby allowing the above-mentioned, 5 to 3 dimensional reduction. To spare all adaptive assembly motions, one might require other materials, and more accurate machining. This latter changes however are not acceptable for economic reasons.

Model-based vision. Passive mechanical constraints of various kinds have been considered, but are not found sufficient for this multi-dimensional case. Consequently, active accommodation, using vision technology and programmable motions are envisaged.
Keyboard shape, and pins positions on the cylinder are defined in the CAD phase, and stored in factory database. Consequently, good flexibility can be gained with a model-based vision approach.

The principle is here to compare actual keyboard images to synthetic database data, accessed through factory network (LAN). From this analysis, a certain quality control can be made, and more importantly, corrective motions can be guided in real-time.

Programmable motion along multiple axes. Final keyboard positioning requires multiple motions; and frequent changes in production are the rule. The standard solution is to take advantage of an industrial robot. Unfortunately, our accuracy and load requirements (error smaller than 0.2 mm, at a nominal load of about 500N) are untypical (the load is high here because the keyboard is held in final position by friction).

Considering that the planar motion can be actuated by three independent axes (no mutual coordination is necessary) a robotic solution is not strictly necessary. Three independent, programmable axes can be set-up, with a dedicated computer control. Two axes provide for lateral and frontal keyboard fine motions, and the third one guarantees proper alignment. All three axes are visually driven in real-time. Fig. 6 shows a schematic view of the set-up.

Final quality control. Current practice calls for a human role in final inspection. The product under review is sometimes imbedded in blind structures, but often remains visible to the end-user. It should therefore be trimmed (clean, shining, of good aesthetic value...). Trimming could be done open-loop, and aesthetic value should result from proper product design. A machine-based visual control of each pin on the cylinder is under study. But the main purpose of the device is to produce (pleasant) soundwaves. Therefore the ultimate quality control would be an audio test. Since melody is in the database, as well as the final optimized note frequencies, an integrated, automatic solution seems feasible, and will probably be considered in the future.

B. Potato operation

Our second case study will address a research project in agrotics, informally referred to as the "Potato Operation" by insiders. The project represents an effort of about 20 man-years, which is mostly developed by research/educational institutes [e.g. 14].

First, a general overview of the project is presented. Then a few aspects relating to §2 discussions will be discussed in the context of potato handling operations and end-effector motions.

1) General overview: Each year, in Switzerland alone, millions of potatoes must undergo viral tests (so-called ELISA tests) in order to avoid spreading infections, which would ruin future crops. Part of the process is already robotized. The rest of the operation is still performed manually.

The current goal is to design a system which would perform automatically the entire process. This translates into transporting to an automated system the manual operation which can be described as follows (see Fig. 7): grasp a potato from bulk or roller conveyors, locate visually germs, and particularly their base, where viral activity is highest. Preferably, choose a large germ, close to one end (the "crown"); drive a sampling device to the area neighboring its base and suck some pulp; finally, deposit pulp into test-tubes, clean the sampling device and reject the potato.

Even though analysis shows that inherent task complexity is not as extreme as it first appear, it remains high, and consequently an advanced solution must be elaborated: robotic motions, under active vision guidance.

The task can be divided in two major subproblems: potato handling, and end-effector trajectory definition.
for blocking heaps. This eliminates height variations. Gravity and roller shape contribute to suppress two rotation angles: the axis of minimum inertia (AMI) finds an equilibrium orientation which is statistically parallel to roller symmetry axis. In summary, a single active motion and passive constraints are sufficient to achieve product singulation, and 6 to 3 dimensional uncertainty reduction.

Independent programmable axes of motion. The remaining 3 degrees of freedom depend on potato variations, and therefore require programmable, sensor-guided axes of motion: variations in potato position along rollers can be limited by a programmable stop, which adjusts path width according to potato types. An additional degree of freedom allows for part grasping, presentation to camera, and final rejection. The third and last degree of motion is necessary for resolving germ position uncertainties around AMI, under guidance of a fixed camera (see active vision, in §3.2.3).

Simple input/output requirements. Some motions can be managed with one-bit signals. In particular, this is the case for roller control and for acquisition/rejection actions. But this aspect is marginal, because powerful control systems are required anyway for other functions.

Passive mechanical constraints. Rollers can easily separate groups of potatoes. A linear motion is provided, with a gate for blocking heaps. This eliminates height variations. Gravity and roller shape contribute to suppress two rotation angles: the axis of minimum inertia (AMI) finds an equilibrium orientation which is statistically parallel to roller symmetry axis. In summary, a single active motion and passive constraints are sufficient to achieve product singulation, and 6 to 3 dimensional uncertainty reduction.

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high semantic content. Even though the problem of finding an appropriate sampling spot bears some similarity to the well-known bin-picking problem (e.g. [15], or see [16] and ref. in it), a novel approach as been proposed. It is described elsewhere, in a specific communication ([14]).

Fig. 10 shows a particular phase when vision processing and object rotation alternate, in order to estimate final germ position in space.

**Fig.10 Iteratively, germs of interest are moved into a plane perpendicular to line of sight.**

**End-effector.** Our problem may seem to require a specialized, application oriented end-effector. But in fact fruit-sampling is a common practice, and tools developed for hand operation can readily be mounted on robot arm (see Fig.11 and [17]).

**Fig.11 Sampling tool as end-effector**

**5-D trajectories.** We have seen how mechanical constraints and visual analysis progressively allow for the accurate location of a sampling spot. Now the end-effector needs be transported to that point, and then pushed forward and retracted with appropriate adaptive direction in space. This calls for trajectories (i.e. coordinated motion) defined in a fifth-dimensional space. This is a typical task for an industrial robot.

IV. CONCLUSION

Industrial automation has been characterized by a tremendous development during the last decades. CIM and IMS are now of major concern for industrial companies. Of all components of these technologies, process automation on the shopfloor is perhaps the most difficult to achieve. This is especially true in the case of handling and assembly operations, which are yet prevalent in economic terms. In particular, even though industrial robots have been around for about 30 years, with constant growth in terms of impact in manufacturing, decisions about their use are still often taken without rational criteria. The paper has attempted to improve this state of affairs, by getting back to basics, providing guidelines, and showing their applicability at concrete, bolts and nuts level through two case studies.

ACKNOWLEDGMENTS

The project benefits from the cooperation of many people. Some are directly involved at the scientific level. Other ones contribute mostly through financial and organizational support.

Within CIFAS project, acknowledgments are given to other partners, in particular: Swiss Federal Institute of Technology in Lausanne (EPFL), Reuge Inc., and Ste-Croix Technical School (ETSC), in Switzerland; Henri Tudor Research Center (CRPT), in Luxembourg. Grants are received from the Swiss Federal Government ("CERS") and from the European Community, within the Eureka/FAMOS program. The Swiss Occidental Center for CIM (CCSO) has also been instrumental in making this project possible.

For the project in agrotics, other partners include several members of the CUI group at the University of Geneva (S. Gil, M. Lefebvre, D. Brunet), of C.W. Burckhardt's team at EPFL (M.-A. Glasssey, C. Baur, E. Natonek) and P. Gügerli, at the Federal Institute of Research in Agronomy at Changins, Switzerland. The project was made possible by a grant from the Swiss National Science Foundation, through the National Research Program for Robotics and Artificial Intelligence.

REFERENCES

APPENDIX. SOME STANDARD SOLUTIONS IN AUTOMATION

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<thead>
<tr>
<th>APPLICATION PARTICULARS</th>
<th>PROBABLE SOLUTIONS FOR AUTOMATION</th>
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<tbody>
<tr>
<td>Simple, one bit sensors or actuators</td>
<td>Programmable logic controllers (PLC)</td>
</tr>
<tr>
<td>Richer information content, number-oriented sensors and/or actuators (n bit)</td>
<td>Microcontrollers</td>
</tr>
<tr>
<td>Complex applications, with significant man-machine communications</td>
<td>Industrial computers</td>
</tr>
<tr>
<td>One or several independent axes of motion; few useful positions along axes</td>
<td>One-shot devices (on/off linear or rotative actuators, usually pneumatic), with PLC control</td>
</tr>
<tr>
<td>One or several independent axes of motion, with many, programmable positions required along axes</td>
<td>Servoed-axes or stepping motors, with microcontrollers or industrial computer, depending on complexity</td>
</tr>
<tr>
<td>Multiple motions, with frequent changes in production</td>
<td>Industrial robots</td>
</tr>
<tr>
<td>Complex trajectories in space</td>
<td>Industrial robots, typically 3 to 6 degree-of-freedom</td>
</tr>
<tr>
<td>Uncertainties in position/orientation (workpieces, tool or peripheral equipment)</td>
<td>Passive mechanical constraints (e.g. self-centering fixtures or grippers, RCC devices, Selective Compliance architectures). See also next point.</td>
</tr>
<tr>
<td>Passive removal of position uncertainties not feasible</td>
<td>Specialized perception equipment (vision, force/torque sensors, depth map sensors, etc.)</td>
</tr>
<tr>
<td>Complex variations in environment</td>
<td>Require functional alternatives that makes manufacturing automation simpler</td>
</tr>
<tr>
<td>Component design can be questioned</td>
<td>Standard trade solution (i.e. machine-tools, measuring robot, automatic guided vehicles, pallet conveyors, etc.)</td>
</tr>
<tr>
<td>One in a class of applications</td>
<td>Sophisticated solutions are necessary (e.g. advanced programming environment, graphic man-machine interface, robotic motions, etc.)</td>
</tr>
<tr>
<td>Task inherently complex (many process parameters, multi-dimensional position uncertainties, etc.)</td>
<td>Parametrized manufacturing systems, and computer integration</td>
</tr>
<tr>
<td>Flexibility required</td>
<td>Try transporting the simple tasks to the more powerful components. Expected advantages include lower investment and part management costs. On the other side, a distributed/modular solution is sometimes preferable, and cycle time may be adversely affected.</td>
</tr>
<tr>
<td>Simple and more complex automation components coexist</td>
<td>Double check! ... it is technically possible to optimize virtually any criterion, But this is useful only if the chosen criterion has a crucial impact on production.</td>
</tr>
<tr>
<td>Some degree of optimization wanted</td>
<td>...</td>
</tr>
</tbody>
</table>