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Robots for micro and desktop factories: examples and experiences

Robots for Micro and Desktop Factories: Examples and Experiences

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Abstract

In this paper we present commercial, prototype, and self developed robots used in micro and desktop factory research implemented at the Department of Production Engineering of Tampere University of Technology (TUT / DPE). We will discuss and analyze our experiences and findings on designing and using robots in micro and desktop factories. Based on this analysis, we will identify possibilities and problems specific to micro and desktop scale robotics.

1   Introduction

During recent years there has been a strong research focus on miniaturizing production equipment which is leading towards micro and desktop scale equipment. At the same time, shorter product lifecycles require faster (re)configuration of production equipment.

By micro and desktop factory equipment we refer to manufacturing and assembly equipment that can be placed on desktop and can easily be moved and handled by human power. For example, the microfactory concept developed at Tampere University of Technology (TUT) [1] uses stand-alone factory modules having outer dimensions of 300 x 200 x 250 mm and a work envelope of 180 x 180 x 180 mm. These base modules can be reconfigured to perform different tasks by attaching different task specific process modules to connecting interfaces on four sides (top, front, left, right) of the base module. However, many commercial implementations utilize slightly larger footprint. For example Master Automation Group desktop cell [2] has outer dimensions of 250 x 500 x 500 mm.

Section 2 of this paper presents several different micro and desktop scale robots. Section 3 discusses problems related to micro/desktop factories and section 4 concludes this paper by discussing possibilities and possible future directions of micro and desktop scale equipment.

2   Examples of Micro and Desktop Scale Robots

In this section we present several different miniaturized robots. Some of them are purely at research level, some are commercial prototypes, but some are already sold commercially. For this presentation, we have grouped the robots to three groups based on their structure: 1) parallel structure, 2) linear axes, and 3) rotary axes. Sections 2.1 – 2.3 show examples of these robots and in section 2.4 we present two case demonstrations implemented with TUT Microfactory concept to show that using micro and desktop robots in real production applications is possible. In section 2.5 we summarize the properties of presented robots.

2.1   Parallel Structure Robots

Many micro and desktop scale robots utilize different kind of parallel structures. Parallel structure adds rigidity and enables robot designer to place motors to stationary parts of the robot structure to lower moving masses. Parallel structure can be implemented in several ways and next we well present several robots utilizing different kind of parallel structures.

Figure 1 shows TUT H-Portal [3] robot which is a belt driven parallel cartesian manipulator developed to be used on top of TUT Microfactory base module (see section 2.4). X and Y movements are implemented with a "H-type" structure where two motors mounted on a fixed frame drive the same closed loop belt. Z movement is implemented with a small ball screw. Working area of the robot is approximately 100 x 100 x 50 mm.
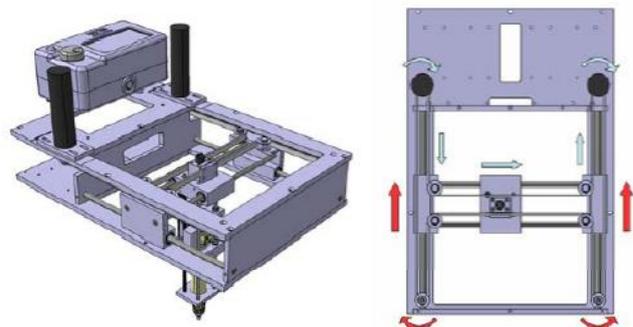

Figure 1 TUT H-Portal robot [3].

Two-arm SCARA is a popular structure in miniaturized robots. Examples of robots using this structure are, for example, Parvus [4, 5], TUT H-Scara [6], and Mitsubishi Electric RP series robots [7]. Parvus and TUT H-Scara are at the moment at research level whereas Mitsubishi RP robots have been commercially available for several years.

Parvus robot [4, 5] shown on right in **Figure 2** is a miniaturized high-precision two-arm parallel robot developed at Braunschweig Technical University in Germany. The primary workspace of Parvus is approximately 36 x 36 x 12 mm (XYZ) but the maximum reach in X direction is

considerably larger. Reported repeatability inside the primary workspace is less than 5.7µm [5]. Left part of Figure 2 shows Mitsubishi RP series robot. Smallest robot in the RP series has 1 kg payload, primary workspace of approximately 150 x 105 x 30 mm and repeatability in XY plane is 5 µm. Although robots appear very similar in Figure 2, their size is different and Z movement is implemented in different ways: Parvus implements Z movement with a single linear axis moving arms up and down whereas Mitsubishi moves only the small shaft vertically. Although Parvus and Mitsubishi robot manipulators are very compact, they use separate controller and amplifier units that are not shown in Figure 2. In some situations, separate controllers and cables from control to manipulator make their use more difficult.

Figure 2 On left, Mitsubishi RP robot [7] and on right, Parvus robot (image from http://www.sfb516.tu-bs.de/english/t2/t2_en.html). Images are in different scales.

Figure 3 shows TUT H-Scara robot which will be mounted on top of TUT Microfactory base module. It consists of two parts: First parallel belt driven "H-type structure" similar to TUT H-Portal robot moves the rest of the manipulator in XZ direction. Second part of the manipulator is a parallel two-arm scara-type robot with XYZW movements. Reach is roughly 300 x 250 x 100 mm. Motor amplifiers are integrated inside the box shown in Figure 3 and motion controller (e.g. a PLC) can be connected on top of this box as shown in section 2.4.
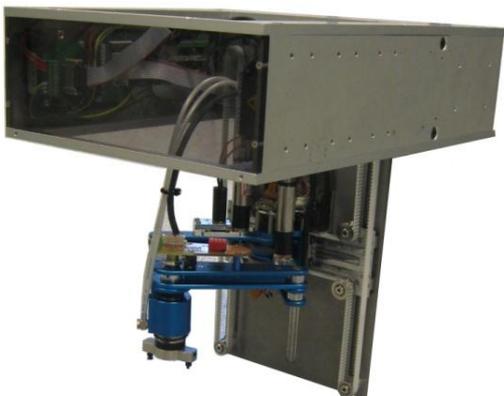

Figure 3 TUT H-Scara robot.

PocketDelta (see **Figure 4**) was originally developed by CSEM (Swiss Center for Electronics and Microtechnology) [8] and is today sold by Asyril company [9]. It uses parallel delta kinematics to produce a working area of 80

mm in diameter and 30 mm in depth. Repeatability is 2.5 µm but payload is only a few grams. Amplifiers and controller is integrated in the same, compact unit on top of motors.
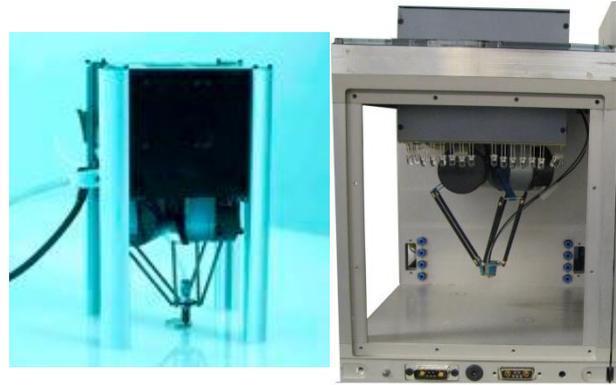

Figure 4 Asyril PocketDelta robot [9] mounted to TUT Microfactory base module.

Figure 5 shows two Fanuc M-1iA series robots [10] utilizing similar structure as PocketDelta. However, their size is considerably larger but larger size means also larger workspace (diameter 280 mm, depth 100 mm, repeatability 20 µm) and higher payload (0.5 kg). These robots are available as 4 or 6 degree-of-freedom models and they use separate control units.

Figure 5 Two Fanuc M-1iA robots [10].

2.2   Linear Axis Robots

Another commonly used way to build miniaturized robots is to use linear axes to form a cartesian structure. **Figure 6** shows one commercial example of a desktop scale production cell implemented with linear axes. MAG Lean desktop cell [2] has outer dimensions of 250 x 500 x 500 mm and it can be configured to perform different tasks ranging from part handling to laser marking. In parts handling applications, payload is 0.5 kg and workspace 140 x 200 x 100 mm. Necessary amplifiers and controllers are integrated to cell (separate box shown in Figure 6 is a laser source). In order to minimize costs, MAG uses several self developed components.

Takashima Sankyo [11] utilizes similar structure based on three linear axes in a bit larger scale to make a desktop process machine capable of machining different materials with micrometer resolution. On the other end of the scale are piezo driven linear axes manufactured by Klocke Nanotechnik. These axes have movement ranges between 5 and 70 mm and they are capable of nanometre resolu-

tion movements. These axes can easily be combined to XYZ manipulators [12] as show in **Figure 7**. Necessary amplifiers and controllers are not shown in Figure 7.
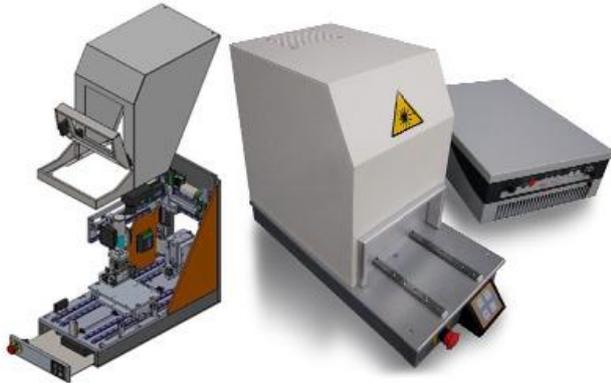

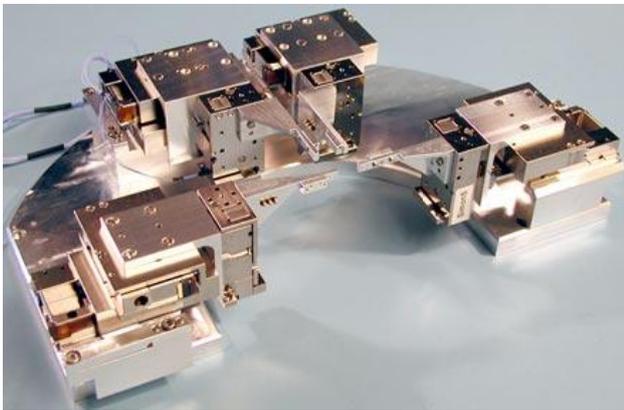**Figure 6** MAG Lean cell configured for parts handling and for laser marking [2].

Figure 7 Four cartesian XYZ manipulators from Klocke Nanotechnik [12].

Linear axis can combined in different ways. Klocke Nanotechnik, for example, has connected X, Y, Z axes is series whereas MAG uses a configuration where Y axis moves the part relative to cell and then X and Z axes are connected in series to move the tool. Third commonly used structure connects X and Y axes in series to move the part under Z axis.

2.3   Rotary Axis Robots

Kleindiek Nanotechnik manufactures high precision, very compact manipulators [13] similar to Klocke Nanotechnik but using rotary axis instead of linear axis. These are meant to be used inside (electron) microscopes to manipulate the sample with nanometre resolution. Model shown in **Figure 8** has 5 g payload. Two rotary joints have 240° range and linear axis has 12 mm reach. Several different tools, including gripper and probe, can be attached to the end of the linear axis. Again, Figure 8 does not show the necessary amplifiers and controllers.

Figure 9 shows an articulated joint robot developed at TUT attached on top of TUT Microfactory base module. This was our attempt to simply downscale existing robot struc-

ture and it proved to be a non-working idea for several reasons which are discussed in detail in section 3.

Figure 8 Kleindiek Nanotechnik micromanipulator [13].

Figure 9 Prototype of TUT articulated joint robot.

Schunk is developing a small SCARA robot and TUT has bought an early prototype of that robot (see **Figure 10**). Manipulator itself is very simple and probably the most interesting component is the extremely compact control unit from Precise Automation (Guidance 1400, [14]). This controller can control up to four motors and it has Ethernet and RS-232 connections and 4+4 digital IOs [14].
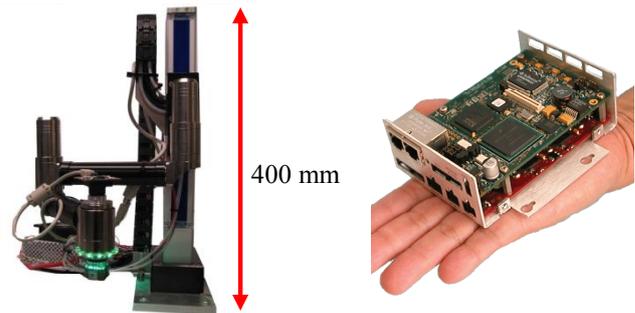
Figure 10 Schunk Scara prototype and Precise Automation Guidance 1400 controller [14]

2.4   Case Examples

Micro and desktop factory research at TUT uses TUT Microfactory modules as a basic building block. **Figure 11** shows a CAD-model of TUT Microfactory base module. The left part of the module is reserved for control electronics and/or auxiliary devices and the larger part on right is the production work space. The top of the base module is reserved for attaching process equipment, for example

cameras or manipulators. Base module has connection interfaces on four sides (top, front, left, right) to enable connecting process modules and other base modules to larger production lines. Some interfaces of TUT Microfactory concept are about to be standardized, for example interface between the base and process modules [15].
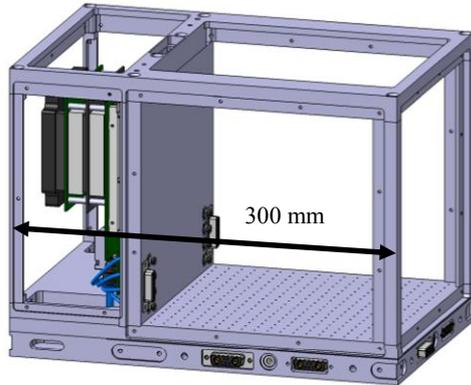

Figure 11 TUT Microfactory base module

One of the first case demonstrations implemented using TUT Microfactory concept was assembling small springs (L = 2.5 mm, D = 0.7 mm) into a hole (D = 0.85 mm) in the corner of electrical component housing (8.6 x 7.0 mm). **Figure 12** shows a CAD model of a flexible spring assembly cell built around TUT Microfactory base module. In this case we used an early prototype of Asyril PocketDelta robot [9]. To see inside the robot working area with a machine vision camera, we had to use a "periscope" consisting of two prisms. Camera and lens were located on top of the module.
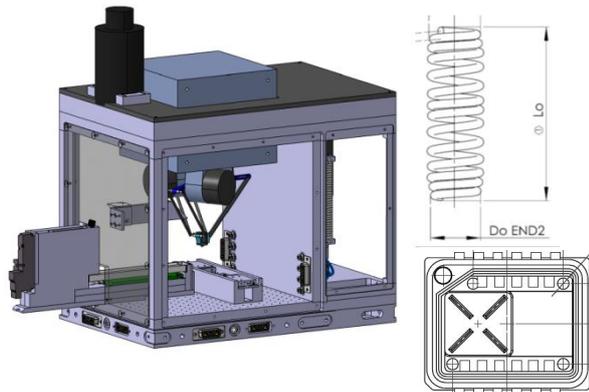

Figure 12 Flexible spring assembly cell and schematic drawings of the spring assembled into a hole in housing.

Latest case demonstration uses TUT H-Scara to assemble a simple product consisting of four parts. **Figure 13** shows this cell which clearly demonstrates the modular structure of TUT Microfactory concept: Manipulator (TUT H-Scara, [6]) module is attached on top of the base module and, on top of that, is the control module that controls the complete cell. A feeder for larger components connects to base module using the same physical interface on the side of the base module.
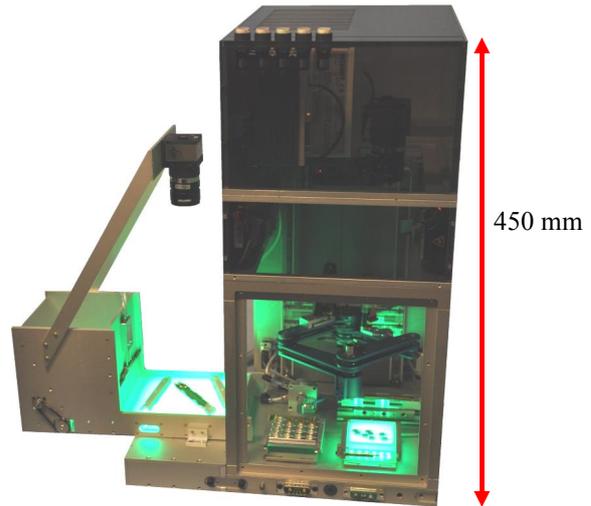

Figure 13 Assembly cell utilizing modular TUT Microfactory concept.

2.5 Summary

Robots presented above are all relatively small. However, they differ in many aspects:

- Size. Even though all robots are small, the scale of "small" differs quite radically ranging from several hundreds of millimetres down to only few tens of millimetres.
- Workspace. Again, range is big – from couple of hundred millimetres down to couple of tens millimetres or only a few millimetres.
- Indented use. Most are meant mainly for part handling applications but some can be configured to different applications. One was designed mainly for machining.
- Degrees-of-freedom. All presented structures have at least three degrees-of-freedom (XYZ) but adding one rotary joint is usually easy. Some models have up to six degrees-of-freedom.
- Speed. Extremely small manipulators are often relatively slow but some of the presented robots are capable of several pick-and-place movements per second.
- Design criteria. Some were designed to reach as high accuracy as possible, some to be as small as possible. For MAG Lean cell, one main driving force was price. For TUT robots, as well as MAG cell, one main criteria has been the integration of necessary control electronics to a compact packet so that separate control units are not needed.

3 Challenges in Designing and Using Miniaturized Robots

In larger, macro scale, systems forces like gravity are dominating. In small systems, gravity starts to become insignificant and other forces such as friction, adhesion, and
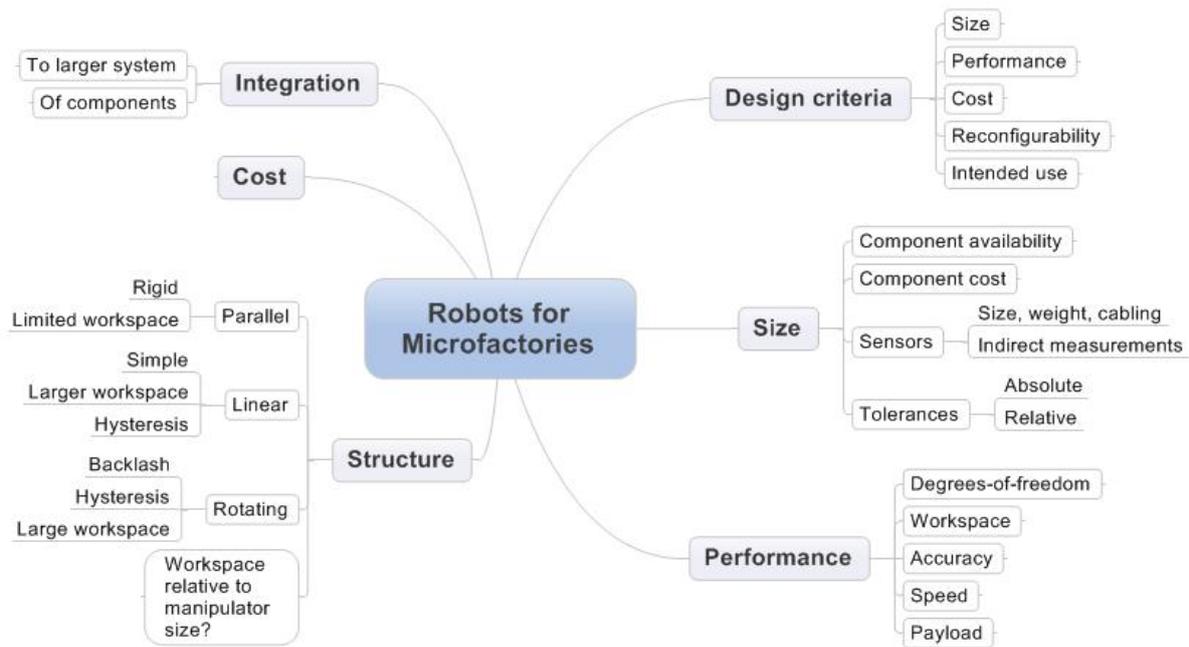
Figure 14 Different factors affecting the design and use of robots in micro and desktop factories.

other surface forces become dominant. Also the mass of actuators relative to the mass of other structures becomes more dominant and therefore scalability of moving mass relative to performance values is a problem in small systems. Furthermore, for example cabling and mountings are more difficult to implement in micro and desktop scale systems than in macro scale. For these reasons, simply downscaling solutions used in macro scale systems to smaller size does not work in many cases. Therefore micro and desktop scale robotics need new solutions.

Figure 14 shows different factors affecting the design and use of robots in micro and desktop factories. Many of those factors are not specific to micro or desktop factories but they have to be considered also in macro scale systems. However, there are aspects that are more important in small systems.

3.1 Design Criteria

One of the first and most important decisions when designing of selecting a robot is to decide the evaluation criteria: Are we looking for minimum size, maximum performance, low cost, or ease of reconfiguration? Robots presented in section 2 clearly have different design criteria and they are indented for different applications. It is also important to consider whether the robot will be used in an automated system or in a semi automated system where also human operators work simultaneously.

3.2 Size

Small size limits some technical solutions because commercial components such as small stone base tables or air bearings often are not commercially available. If you can find commercial components, their price increases rapidly

when the size gets "too" small. **Figure 15** illustrates our estimations of component size versus price in different scale systems.
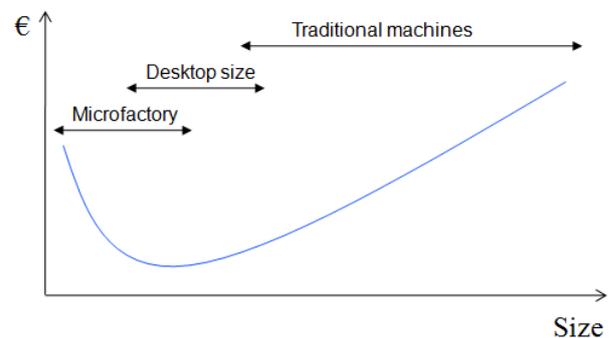
Figure 15 Component size versus price.

Sensors are difficult to integrate to small systems because of their size, weight, and cables needed. Therefore indirect measurements based, for example, on machine vision are often needed.

When manufacturing small parts (e.g. gearwheels), the absolute manufacturing tolerances remain the same as when manufacturing larger parts. However, when part size gets smaller, the relative tolerances become worse. Tolerances cause backlash, play, and hysteresis which decrease performance values.

3.3 Structure and Performance

Many miniaturized robots use different parallel structures. Main advantages of parallel structures are rigidity and lower moving masses because motors are not included in the moving masses. Light moving masses enable, in the-

ory, high accelerations. In practice, however, delicate mechanical structures limit accelerations and thus movement speeds. Main disadvantage of many parallel structures is limited workspace.

Robot structures based on linear axes or rotating joints often have larger workspaces but are more sensitive to backlash and hysteresis than robots based on parallel structures. In small systems, friction becomes dominant force instead of gravity and, as designers of Parvus robot noticed, frictional torque can cause elastic backlash even though gears themselves are backlash free [5]. Because higher friction means that less force/moment is available for moving the payload, robot payload decreases rapidly.

Large manufacturing tolerances relative to component size combined to problems with backlash and hysteresis mean that robot repeatability does not scale down as system size is scaled down. In fact, in small systems the repeatability relative to system size is in many cases quite significantly worse than in larger systems. Multidirectional accuracy and path accuracy might be even bigger problems.

Robot workspace has similar scaling problems. Because actuators and sensors remain relatively large and cables need space, robot workspace relative to robot size is often worse in small scale robots than in conventional size robots.

3.4 Integration

Integration can be understood in two ways. First one is the integration of components to get smaller size, better performance, lower cost, etc. Second way is to think how robots can be integrated to larger manufacturing systems.

Miniaturizing robots, or any other components or systems, often requires custom made and/or integrated and specific components. Examples of these could be integrating control system and motor amplifiers to one compact housing, integrating sensors directly to actuators, etc. Cables should be reduced to minimum because they are difficult to implement in micro and desktop scale.

Other aspect of integration is using and integrating robot as a part of larger manufacturing systems. In this respect, compact size of not only the manipulator part of robot but also of the control system is important. Many of the robots presented in section 2 are very compact, but in addition to the manipulator, there is a not so compact control system a cables connecting control unit to manipulator.

4 Discussion and Conclusions

Miniaturized production equipment and systems can offer numerous advantages. It is expected that miniaturizing production equipment will lower production costs by reducing needed production floor space (or by enabling more capacity in the same floor space), reducing big investments, and by reducing use of energy and other resources. Savings can be even bigger in processes needing clean rooms. Small system size and better reconfigurability will enable faster changes in system layouts and shorter capacity ramp-up times.

Some micro/desktop systems will continue developing to direction of ultra high precision and/or small size. However, at TUT we see that one very promising future direction for micro and desktop systems will be relative simple and low cost systems that are used in semiautomatic systems. In these cases, micro/desktop systems will work together with human operators by performing simple tasks right next to the operator while operator performs more complicated tasks. One example could be that an operator manually assembles a product and then puts it to a desktop screwing machine that finalizes the assembly while operator is assembling new product.

This kind of systems need to be easily moveable from place to place, easy to expand, and easy to reconfigure to changing requirements. They also need to be low cost. However, they do not need to have high capacity or to be capable of very complex operations. This means that, instead of individual miniaturized machines, we need system concepts with standardized interfaces between modules. With plug-and-produce capability, these modules can then be used to automate production process step by step or to increase production capacity in small steps. As **Figure 16** shows, this kind of concept of simple, low capacity but also low cost modules would decrease investment steps when needed capacity changes compared to bigger, more expensive machines with higher capacity. This development has already taken place in circuit board manufacturing and therefore we do not see any reason why it would not be possible also in other manufacturing fields. TUT Microfactory concept is one example of how modular structure with standardized interfaces can be implemented.
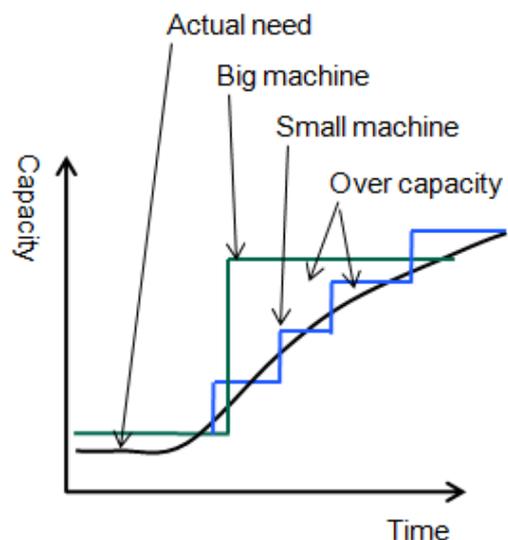

Figure 16 Needed capacity and investment steps.

5 Literature

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