1

Highlights in mechatronic design approaches

From the 'first time right' approach to iterative design - where mechatronic design meets the maker movement

Edwin Dertien and Stefano Stramigioli

Robotics and Mechatronics group
Faculty of Electrical Engineering, Mathematics and Computer Science
University of Twente, Netherlands
{*e.dertien*}*@utwente.nl*
{*s.stramigioli*}*@utwente.nl*

Abstract

In the recent years a major change in the engineering process of mechatronics and robotics has taken place. In various design oriented laboratories around the world a shift can be recognised from a focus on analysis, simulation and modelling combined with outsourcing hardware design to the use of digital fabrication tools (laser cutter, 3D printer) allowing a cyclic (iterative) design process inside in the lab. This chapter aims to give an overview of the impact of this change, using many examples from various projects, and will share some insights and lessons learned for facilitating and implementing this process.

1.1 Introduction

The term Digital Fabrication has been introduced (or deepened) by Neil Gershenfeld [9] in his book 'Fab: The Coming Revolution on Your Desktop'. The topic (and term) are very popular describing the changes currently taking place in the world of engineering and academia. A recent publication by Bezzo et al., [2] lists myriad new ways of manufacturing robotic parts, new technologies, materials and unprecedented levels of integration. The proposed lab format by Gershenfeld has not only inspired hundreds of 'FabLabs' around the globe, but also inspired research labs worldwide to (re)incorporate manufacturing.

Besides offering new materials, technologies with a high level of integration (soft materials with embedded sensing, multi-material print in one run) the technology of digital fabrication also allowed a process optimisation with a large impact in our lab: Kaizen in Mechatronics. The term Kaizen (Japanese for 'improvement') has become famous by Toyota's successful business strategy, described by Masaaki Imai [11]. This notion has been used as basis for many iterative design processes such as SCRUM in software development. The application of this principle to mechatronic design has yielded systems in our lab with a level of integration which was hitherto unthinkable in lab prototypes.

Thanks to concept of digital fabrication, 3D printing technology and other (2D) manufacturing techniques using laser cutter, CNC milling machines and the like are changing the way mechatronic research is being conducted. In this chapter we will discuss the changes it has brought to our lab, the changes we see worldwide, some of the high potentials and risks that come with it. For the tools to have maximum impact we will argue that the criteria *accessibility, availability and visibility* are key in successful implementation and maximising potential of this technology. As most fundamental benefit we see the possibilities of rapid iterative design cycles in mechatronics. Most impact in future will is expected from tight integration of these rapid design cycles in physical hardware with existing technology for simulation and development.

As one of the illustrative cases in this chapter the development of a pipe inspection robot for small diameter gas distribution mains is used. This project has been described in the author's thesis [5].

1.2 Rapid Iterative Design Cycles

Every design process (if not every scientific process) has a cyclic nature. Based on observation a hypothesis is formulated which is proven (or disproved) by designing an experiment and evaluating the results. Based on the observed outcome a new hypothesis can be formulated and the works continues.

For design and engineering normally a similar approach is taken. For a given problem a solution is designed which is analysed, tested, simulated, (and if everything looks promising) constructed, built and evaluated. The role of engineering as an academic discipline is discussed for example by Herbert A. Simon in his book 'The Sciences of the Artificial' [17], who describes the divide between teaching 'design' and teaching 'analysis'. The method of engineering is investigated in further depth by, among others, Schön in ‘The Reflective Practitioner’ [16] and Vincenti in ‘What Engineers Know and How They Know It’ [20].

This chapter does not intend to contribute to the discussion on the differences between engineering and academia or to present a detailed analysis of how the choice of *method* of design and engineering influences the end result. Yet the last decade a major change in engineering process has taken place. This change might be the influence of the *zeitgeist* or a deliberate choice, or both.

Since engineering hardware is expensive the realisation of a given system has to be right ’the first time’, so all major effort goes to validation of the concept and implementation choices beforehand. This is a very complex process when there are many unknown variables, for instance specific details on the environment in which a given system has to operate.

In the mechatronic approach as practiced in our lab, for example described bij Schipper [15] in 2001, a lot of effort, time and energy is devoted to the analysis and testing of a potential solution, before considering constructing a prototype for evaluation. A normal course of action for a project was to devote most of the time to simulation of a possible solution (and thereby improving the modelling and simulation tools) in order to get the expensive hardware right the first time.

This ’first time right’ approach has a lot to say for it. It minimises costs of professional designers, constructors, expensive parts since the whole exercise has just to be taken once.

1.3 Simulation

The typical modelling and simulation tool of choice for mechatronics at our research group was, besides the ever popular Matlab, a package of a spin-off company from the group called 20sim[1]. 20sim focuses on energy based modelling of dynamical systems. It provides excellent toolboxes for 3d mechanical structures calculating inverse and forward kinematics, all using a port-based approach so forces, torques, linear and rotational velocities in 3D space are modelled as twists and wrenches as described by Stramigioli and Bruyninckx [18].

A large number of projects in the past have proven the validity of this tool. One of the authors personal experiences was the design and construction of a passivity based biped robot called ’Dribbel’ shown in figure 1.1, a 10 kg planar walker with knees [6].

An interesting problem in port-based modelling is the simulation of hard contacts such as the impact of robot feet on the ground. In order to allow the simulation to work the model has to be power continuous (no discontinuities such as suddenly

[1] http://www.20sim.com

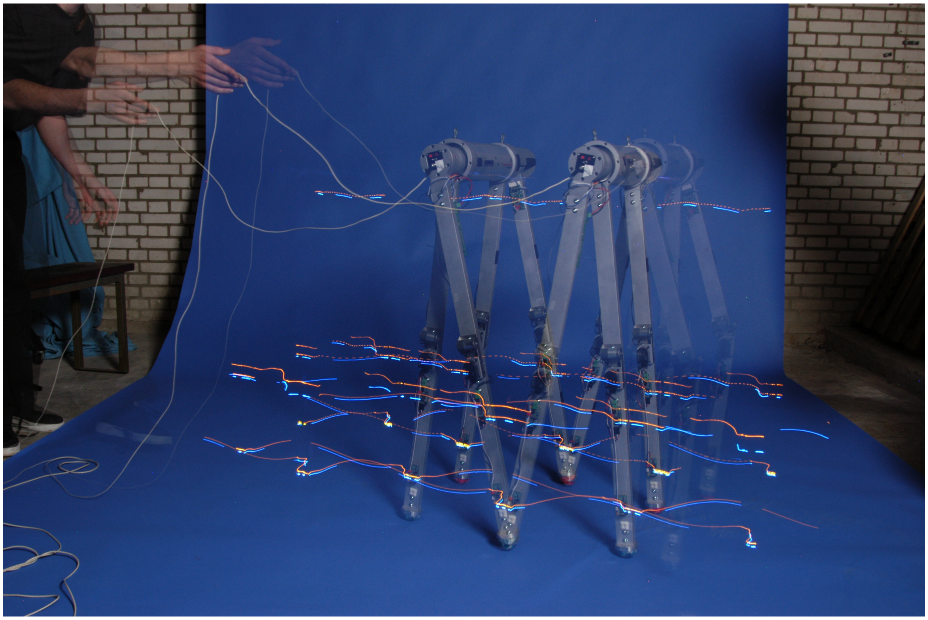


FIGURE 1.1 Planar passivity based biped ’Dribbel’

setting a velocity to zero or resetting the position integral are allowed). That means that for hard contacts normally a spring-damper model is introduced (referred as the Hunt-Crossly model), its application to robotics modelling discussed recently in the work by Diolaiti et al. [8]. In this model as upon impact a spring-damper combination with high damping and very high spring constant.

After realising the robot and matching the walking performance with the simulated outcome both seemed to match fine. Figure 1.2 shows both the walking robot and simulation. One of the outcomes of the simulation was that the simulated robot walked much better when spring constant (and especially damping) in the contact model were reduced. This makes sense in a way. Damping takes away energy from the walking motion which might be returned on impact in order to improve the walking motion and make it more energy efficient. Modern prosthetic devices using springs made famous by the ’Blade Runner’[2] verify this.

The real-world implications of this ’faulty contact model’ were verified by outfitting the robot with bouncing balls as feet (rubber with very low damping) which allowed for a smooth, very energy efficient (and rather bouncy) walk. In this project

the ’first time right’ approach roughly worked. The mechanism was simple enough (4DOF in planar simulation) where the most critical factor for matching the model with reality (the contact model) actually proved to be a useful design criterion.

[2] https://en.wikipedia.org/wiki/Oscar_Pistorius

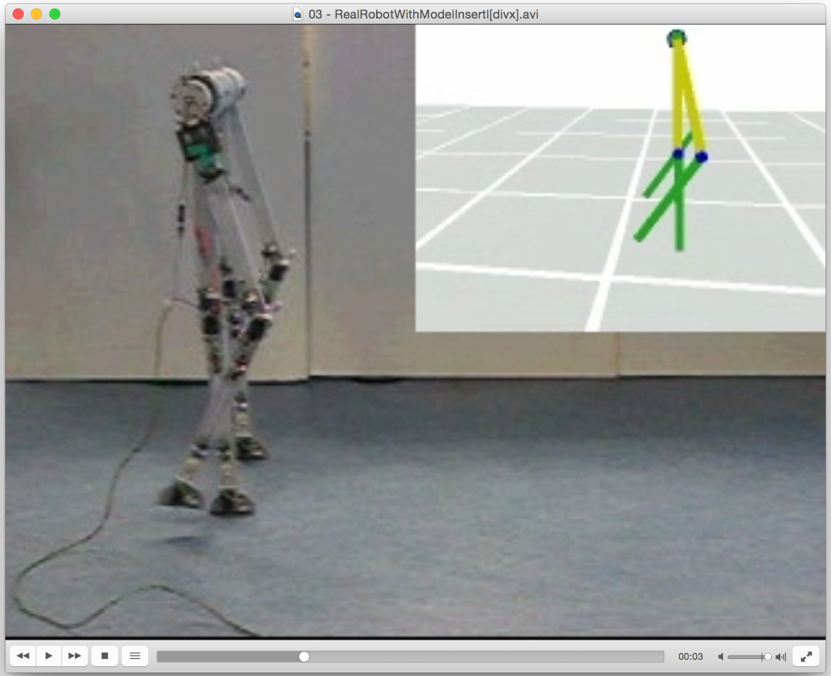


FIGURE 1.2 Matched simulation of 'Dribbel' in 20sim

In a next project (starting 2006) a similar approach was taken. A project was started to develop a robot for inspection of small diameter gas distribution mains as described by Pulles et al., [13], in collaboration with Dutch gas grid quality agent KIWA[3]. Again much effort was devoted to designing and evaluating a number of concepts, simulation of the most viable ones, finally selecting one of the simulated concepts for realisation. The detailed engineering of a prototype for this concept took a long time. Since non of the mechanical parts could be obtained as Common Off The Shelf (besides the chosen DC motors), every part needed detailed construction drawings. Most of the parts had to be outsourced for production. This meant a 2 month gap in the design process waiting for the mechanical parts. Electronics for control of the robot had been developed simultaneously (the hole point of a mechatronic exercise) so the time 'waiting' could be spent on continuing with software, testing electronics, etc. After completion of the mechanical prototype it still took half a year to conduct the first functional tests, and another year to solve all

[3] http://www.kiwa.nl

tiny (hardware) related issues necessary to have the robot move to its designated obstacle course which could be presented only much later at the ICRA conference in 2011 [4]. Needless to say that an improvement of the development process would be highly valued at that time.

1.4 Robot Makers

The project started out with a similar mechatronic design process as described with the previous case (the walking robot), but continued with a more 'maker' inspired methodology as described by Chris Anderson in his book 'Makers, the new industrial revolution' [1]. The maker movement refers in this case to the large worldwide group of DIY enthusiasts, open hardware and open software designers, hobbyists and other people that 'build' things. O'Reilly media coined the term 'makers' with the start of their magazine 'Make:' in 2005 and the organisation of gatherings of makers and builders called 'Maker Faires' in the US[4]. Also the recent publication by Bezzo et al. [2] has been named 'Robot Makers' with the intended affiliation.

Although strictly speaking many of the rapid prototyping technologies that are discussed in this chapter have been available for use throughout the entire span of the developed pipe inspection robot, they have actively used since 2010. This progression appears to coincide with the rise of aforesaid 'maker movement', but there might not be a strong causal connection that can be claimed. For example, in 2006 at the start of the project, a *Stratasys Dimension 3D printer*[5] was located at the University in the modelling workshop used for industrial design students. The use of this machine was effectively never considered for production or prototyping of the robot, although it could have done the job equally well as a machine that was bought much later, but places *inside* the robotics lab, making it available, accessible and visible for all projects.

1.5 Example case: pipe inspection robot 'PIRATE'

In this section a comparison will be made between an earlier developed prototype (shown in figure 1.3 and a rapid, iterative developed prototype of the same project, in this case the design of a robot for inspection of small diameter gas distribution mains. Among other things, an additional level of creativity enters the way a product is designed when allowing other technologies and also different design methodologies to enter a hitherto linear design process. At the University of Twente the Bachelor course Creative Technology tries to put different design paradigms to practice, sparking a discussion about the way chosen development methodologies

[4] http://en.wikipedia.org/wiki/Maker_culture
[5] http://www.stratasys.com/

influence engineering science as also for example discussed by Resnick et al. [14] at MIT.

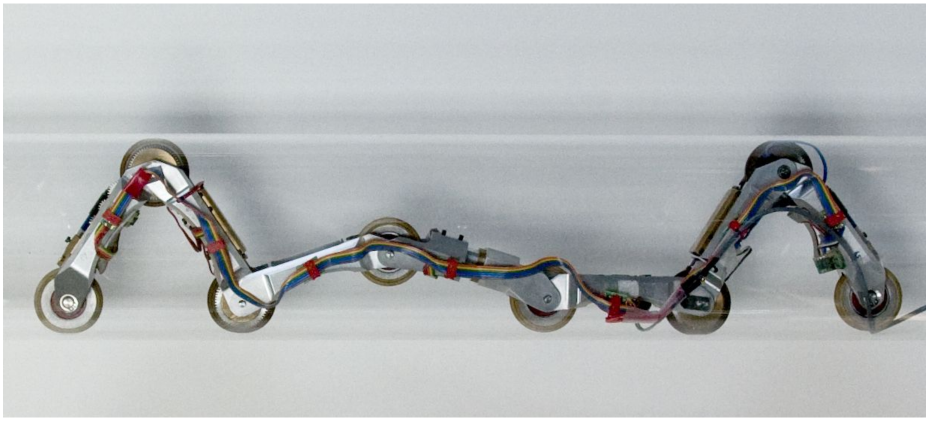


FIGURE 1.3 First incarnation of a 'clasically' engineered prototype of the Pipe inspection robot

The first prototype has been designed using the mechatronic design method as used at that time at collaborating project partner DEMCON, which underlying philosophy is described in the work by Schipper in his thesis [15]. Physically housed in the same room, the mechatronic design team consisting of a mechanical engineer, electronic engineer, software engineer and systems engineer designed the robot in a collaborative effort under supervision of two senior engineers. This initial project followed the classical engineering approach using decomposition, realisation of sub-components, integration and eventually testing and evaluation.

A modular design approach was in this case interpreted as designing separate modules with each their specific function. This allowed the engineers to narrow their focus 'per module' instead of focussing on an overall design. In later prototypes a setup using mostly identical modules has been chosen.

The approach was mostly aimed at a 'first time right' approach, meaning that once all the mechanical design drawings had been fixed, the drawings were processed for manufacturing, the design drawings were shipped to a manufacturer and after a relative long period (8 weeks) of production and shipment a start could be made in assembling the robot.

Especially the amount of wiring necessary for the motor control boards and the inflexible installation took a lot of time and effort. Eventually the wiring had been mounted at the outside of the modules as shown in figure 1.4, acting as obstacles during tight manoeuvres in pipe joints. Although the placement of the wires had been discussed during the design phase, the choice had to be made to postpone this for later, since taking in the routing of cables and placement of connectors was a too large effort in this 'first time right' approach. All in all the 'first time right' approach takes a long time and lacks possibilities for quickly exploring alternatives.

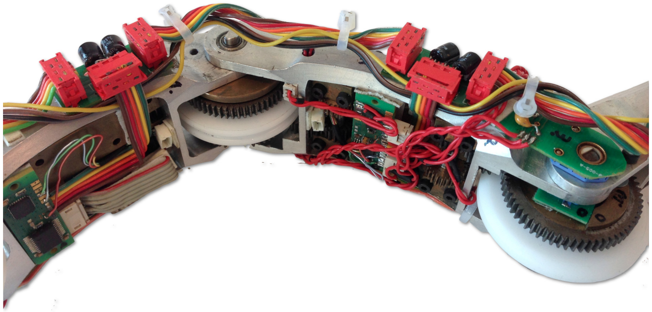


FIGURE 1.4 Close up picture of the wiring of prototype 1

1.6 Additive Manufacturing

During the course of the project a change took place in the world of desktop fabrication. Due to this maker movement and the FabLab[6] concept, 3D printers, laser cutters and CNC routers have made a leap from the factory to the desktop. *Accessibility*, *visibility* and *availability* of production methods in a lab or at home increase the usage dramatically. This point has been made clear in the work by Mader and Dertien [12] in the context of student assignments for the bachelor track 'Creative Technology' at the UT. Similar results could be observed in different generations of students working on design assignments, having access to standard production facilities nearby (i.e. wood workshop, electronics workshop), or having access to production facilities on sight (i.e. -just- one laser cutter). Based on these observations we stated that:

Only when a tool or machine satisfies the following three criteria it will have a serious impact on the design process:

- the machine or tool needs to be *visible*
- the machine or tool needs to be *available*
- the machine or tool needs to be *accessible*.

The reverse is also true: when a machine is not visible (as in, present in the lab) the machine will not be taken into consideration. When a machine is not available (as

[6] http://en.wikipedia.org/wiki/Fab_lab

in, constantly in use), other options will be sought. When the machine is not accessible (as in, difficult to use, steep learning curves, high threshold, no information) the machine will only be used by the happy few willing to learn and adapt.

All of these arguments might explain why in an earlier stage of the project the printer in the modelling workshop of Industrial Design was not considered: it was not visible (different building), the availability was unclear (sometimes days of work by Industrial Design students, sometimes nothing) and information on workflow, file types and necessary preparation was missing.

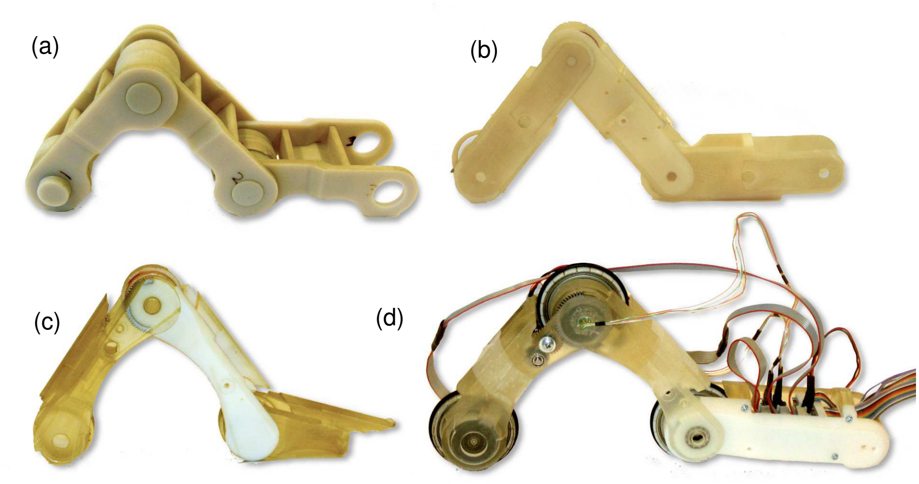


FIGURE 1.5 Four iterations of modules of the pipe inspection robot.

1.6.1 Design iteration through 3D print

After the some successful trials of the robot taking mitre-bends (shown in video accompanying [4]), it was clear that no further progress could be made with the first prototype. The main reasons were the weight of the design, lack of traction torque and mostly unreliable control electronics.

An Objet Eden 250 machine was installed in the laboratory for Robotics and Mechatronics (RaM) lab in september 2010. Based on earlier stated observations this machine was bought and placed deliberately inside the working environment of the students (and not, perhaps more conveniently, in a closed cabinet, a soundproof room or one of the workshops in the building). The machine was deliberately not planned and scheduled for production (for third parties). This means that the machine was almost always immediately available for an overnight manufacturing run of new parts. The machine accepts standard STL drawings which can be generated directly from SolidWorks. No further post-processing of the drawings is necessary, so the accessibility is high.

It took a long time before the first prototype (2006-2008) was ready for testing (first time right constraint). After manufacturing of the parts the assembly took also a long time due to small deviations in manufacturing, small errors in design, the lack of availability of necessary tooling and technicians, etc. This is in strong contrast with the process during the project by Borgerink [3] where prototypes have been produced on an almost two-weekly basis. Figure 1.5 shows three prototypes which have been subsequently designed and tested. It can be argued (and defended) that the final module design presented in this project has reached at least an equal level of complexity and completeness as the first prototype shown in figure 1.3.

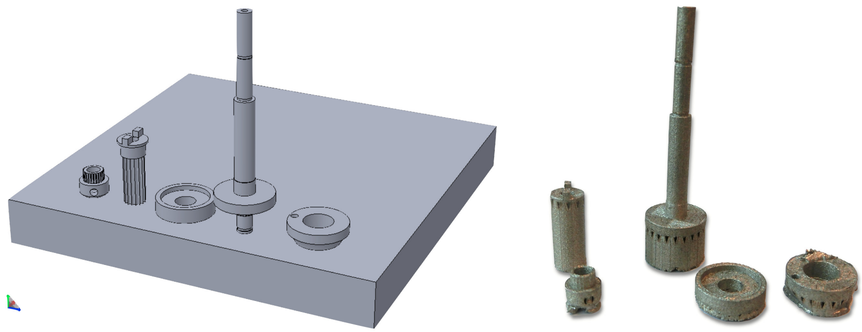
The first two models (a) and (b) in figure 1.5 used printed materials for joints, the third prototype (c) and the final model (d) allowed for metal inserts such as bearings and gears. While the first prototype shown is rather bulky and not capable of moving inside even the largest of the required pipe diameters, it still yields valuable information on necessary wall thickness, placement and aligning of the drive motors, available space for the bending drives, etc. Each iteration adds more functionality and solves more design constraints. The main merit of this process is that not all design constraints have to be solved in one go, but can be tackled incrementally.

1.6.2 Printed metal parts

In an experiment to bring the additive manufacturing technology even further in the design process, an attempt has been done to also produce the mechanical shafts and bushes on a 3D printer. A print service nearby featured a *Concept Laser M3 Linear* machine capable of working with stainless steel. Since the tolerances of the print quality were not quite specified (everything between 0.2 and 0.6 mm deviation) in both shape and thickness, an experimental batch of the needed mechanical parts has been produced.

In order to compensate for size deviations, the shafts have been printed incorporating a number of grooves on the surface - which could act as both centring aid and 'compressible' structure for an axial fit of gears and bearings. The height of the grooves has been set at +/- 0.4 mm with respect to the original diameter in order to accommodate for most of the specified deviation range.

The shafts have been printed in vertical orientation (the print-bed could be much lower and the process shorter) instead of printing the shafts horizontally. Due to the support material that needs to be printed, a shaft could turn out strongly imbal-



(A) the parts on the build platform (B) the printed batch

FIGURE 1.6 The five experimental metal drive parts

anced due to the added material.

Figure 1.6a shows the parts generated in SolidWorks in the desired orientation on the build platform for print. The resulting parts are shown in figure 1.6b. After the printing, the support material needs to be removed. Figure 1.7 shows an extensive section of cross-hatch printed support. Figure 1.8 shows the last bit of support that is removed. After removing the support, the remaining bit needs to be sanded and polished. Unfortunately this proved to be a very time consuming task, comparable to turning the complete parts by hand on a lathe (by a skilled technician).

The complete realised batch is shown in figure 1.10. The surface of the printed material remains quite rough, as can be seen in the pictures taken through a microscope (magnification set at 40x) in figure 1.9. Figure 1.11 shows a printed driveshaft with mounted oldham coupling plate and mounted worm gear. The grooves allow a reasonable tight fit although for the final assembly glueing is necessary. Also with the (CNC) produced metal parts gluing is a necessary step in the final assembly.

Figure 1.12 shows the comparison of two shafts. The gears that are fitted are stock components of HPC. Note that the thread cut in the spring shaft (the long shaft shown in figure 1.12) had to be cut by hand after printing. The printing quality cannot offer enough level of detail to print a reliable thread, especially not when after print some support material attached to this thread needs to be removed. To conclude, with the current printing technique the necessary level of precision for the drive parts cannot be reached. Also the price and the required time for printing and post-processing is too large to make it a part of a rapid-cycle iterative design process.

FIGURE 1.7 Shaft with the support material that needs to be removed

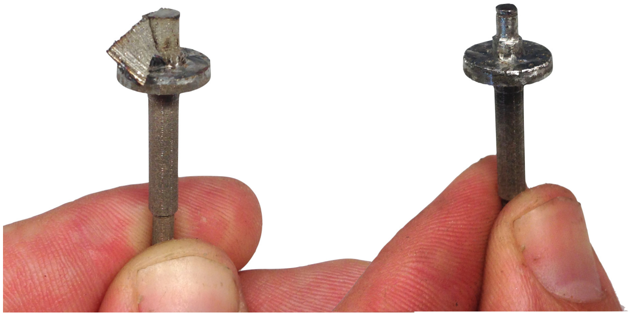


FIGURE 1.8 The final stage of preparing the shaft where the metal support material is 'peeled' off layer by layer

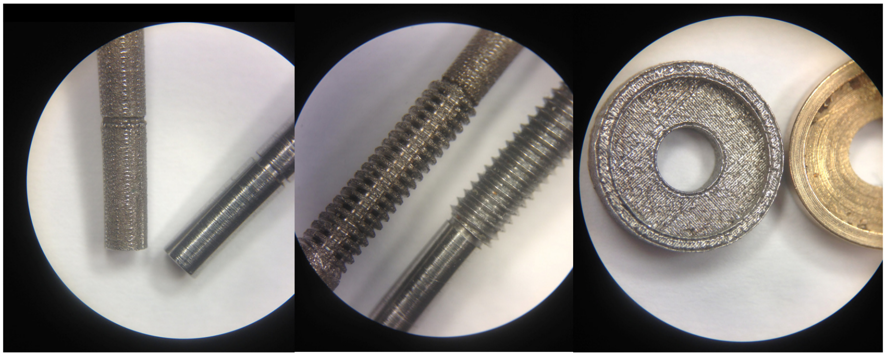


FIGURE 1.9 Comparison of the printed shafts and the parts produced on (CNC) lathe

FIGURE 1.10 Finished parts (after some considerable rework using a rotary tool)

FIGURE 1.11 Drive shaft with fitted oldham coupling plate and worm gear

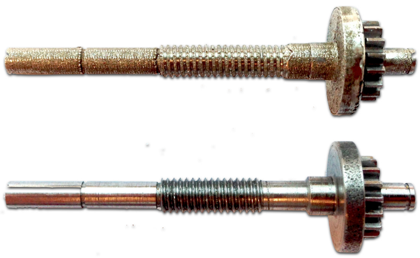


FIGURE 1.12 Two drive shafts, one printed, one produced on (CNC) lathe

1.6.3 Body material

The body structure which was originally printed in house on the *Objet Eden 250* machine has been printed for the final modules on a *FORMIGA P100 SLS* machine offered by an external print service. The main body parts are printed using PA3200: nylon reinforced with glass fibres, shown in figure 1.13. Since it is not easy to adapt or rework the fibre reinforced pieces, the parts which need some post-processing such as the wheels and the motor casing are printed with PA2200: 100% nylon which can be sanded and cut reasonably well.

FIGURE 1.13 Three modules printed in PA3200

1.7 Design for laser cutter

A totally different prototype for the same project using omnidirectional wheels described in [7] has been designed, constructed and tested in two weeks. As production method a ‘flat’ design which can be fabricated on a laser cutter has been chosen.

Following the ‘digital fabrication’ theme propagated by the Fablab movement, in 2010 the lab acquired a *Trotec Speedy 100* laser cutter. This machine can cut and engrave most flat materials excluding metals and other good thermal conductors and materials containing PVC. Also for designing pneumatic systems this machine has proven to be extremely versatile as shown by Groenhuis [10] in his recent work on MRI compatible robot systems.

One remarkable feature of designing ’flat’ robots is that the drawing functions both as design manual and CNC file at the same time. The drawing *‘is’* the design. One could select the vector drawing from the digital version of this thesis in figure 1.14 and send it directly to a laser cutter, resulting in almost all necessary mechanical parts for the frame.

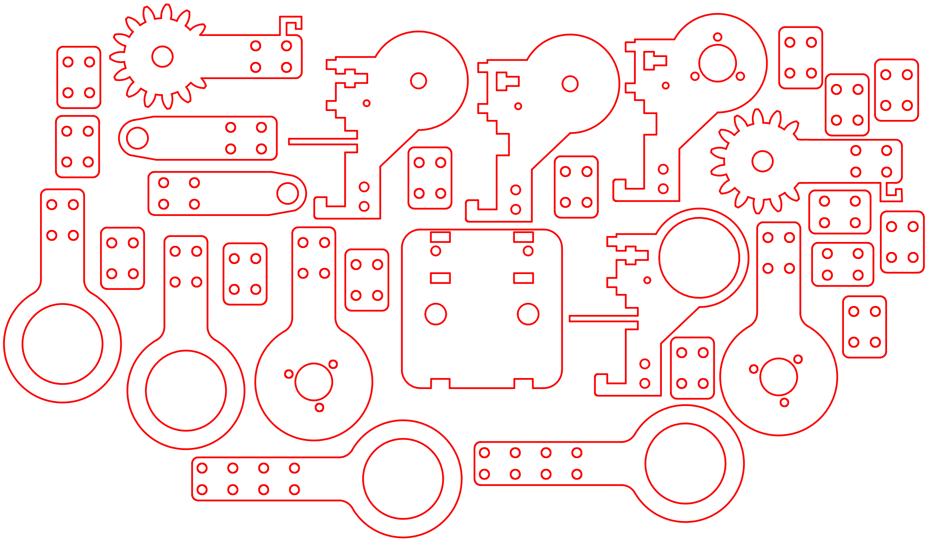


FIGURE 1.14 Drawing of the parts for the omniwheel prototype

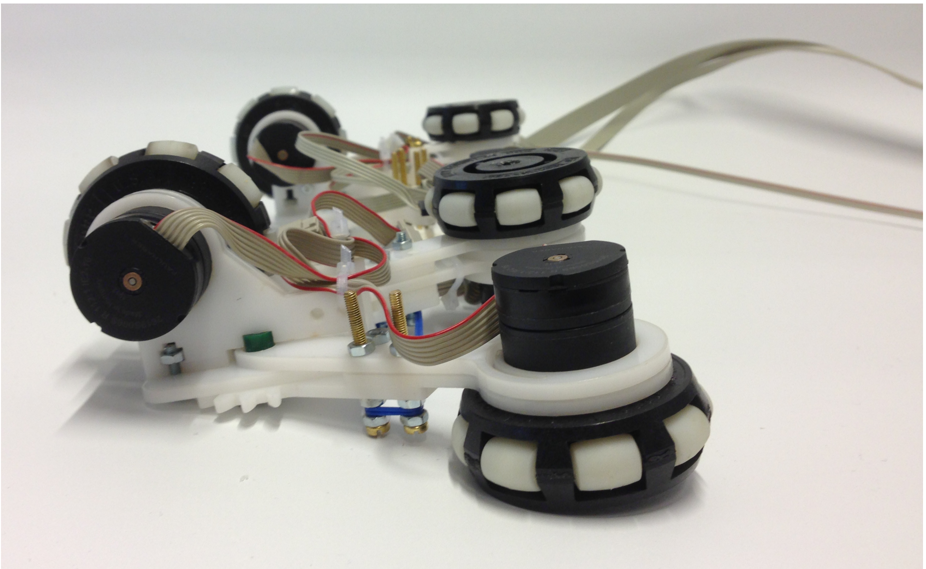


FIGURE 1.15 Detailed picture of the flat construction of the omniwheel prototype

1.8 Open micro controller design

During the course of the described project a different invention gradually took the world of education and design. *Arduino boards* and integrated development en-

IDE

vironment (IDE) have become a 'de facto' standard for Physical Computing and Interaction Design. Although primarily aimed at prototyping, hobbyists and 'makers', the board is also popular for rapid prototyping in mechatronic engineering disciplines. The wide variety of available extension boards, software libraries and support materials allow the board to be used as quick, standard building block.

From wikipedia[7]: *'Arduino started in 2005 as a project for students at the Interaction Design Institute Ivrea in Ivrea, Italy. At that time the students used a "BASIC Stamp" at a cost of $100, considered expensive for students. Massimo Banzi, one of the founders, taught at Ivrea. A hardware thesis was contributed for a wiring design by Colombian student Hernando Barragan. After the wiring platform was complete, researchers worked to make it lighter, less expensive, and available to the open source community. The school eventually closed down, so these researchers, one of them David Cuartielles, promoted the idea.'*

For the robot a motor control board needed to be developed, small enough to fit the minimal space available in the 3D printed housing.For the first robot model a design was made using development tools offered by the controller's manufacturer (in this case a chip and IDE made by Atmel). For the second series of prototypes the choice was made to make it fully compliant with the Arduino development environment.

The change in development process of electronics with respect to the first prototype and the subsequent boards is large. Although in principle similar hardware (AVR familie microcontrollers) and similar software (GNU GCC) has been used, the change in development process of electronics by the Arduino system is comparable to the change in development process of the mechanical system by the 3D printer. The Arduino tool set (boards, bootloaders, IDE) makes the process very accessible, and even more important: easily distributable. Many example projects are visible on the internet, libraries are readily available. This speeds up the development process dramatically.

1.9 Distributed control architecture

The developed modular hardware of the pipe inspection robot consist of many identical modules and the large number of degrees of freedom (at least 11 motors per robot) have caused something which is normally rare in prototype development: series production. The robot uses six identical drive motors with identical wheels, bearings and couplings, four identical bend motors with four identical gear sets and spring shafts. The robot uses eight identical magnetic position sensors and six identical motor control boards (not counting the motors, sensor boards and

[7] http://en.wikipedia.org/wiki/Arduino

motor control boards which have to be added for an active camera module). Since wiring all these items to a central control board is simply not possible regarding the available space, also a modular approach was taken in developing the electronics, resulting in a distributed control architecture as shown in figure 1.16.

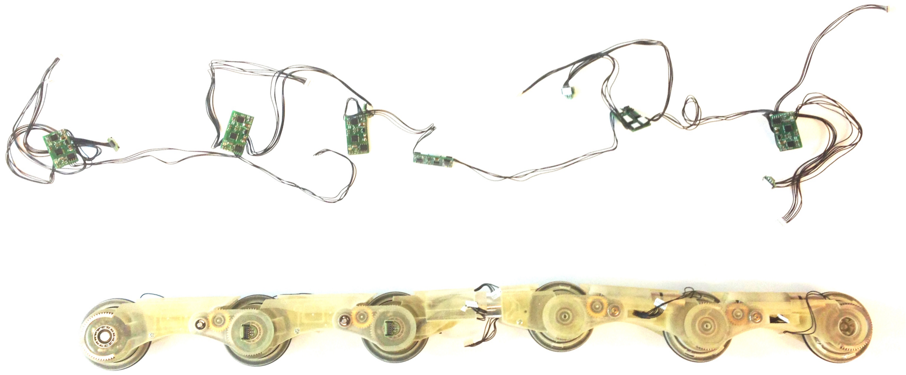


FIGURE 1.16 The robot's 'nervous' system consisting of a number of control nodes

The PCBs necessary for these control nodes have been designed using the open source package KiCAD[8] and populated and reflow-soldered in house. Since the PCB pooling service produced stencils for application of solder paste, only custom tool to fixate and outline the stencil with respect to the PCB was needed to do precision application. Again, the tool was produced on the laser cutter (shown in figure 1.17). Also the reflow oven shown in figure 1.18 which has been used was an Arduino controlled converted toaster oven.

Figure 1.19 shows the control board and the sensor board which have been developed using only open source tools for development. The relative 'ease' of production, the small development time, the simplicity with which these designs can be designed, deployed and distributed is striking, when comparing it to the (relative) slow pace of development only a short time before.

1.10 Conclusion

In this chapter a wide number of techniques have been shown which are in itself not quite new although are gradually taking their place in the design process of mechatronic systems, allowing rapid development cycles. Visibility, availability and

[8] http://www.kicad-pcb.org

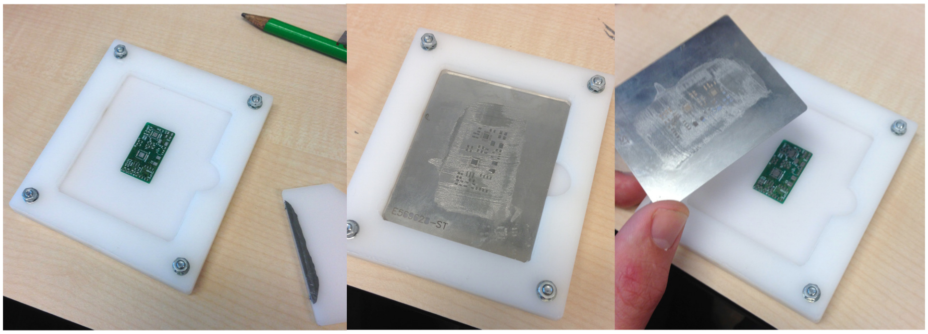


FIGURE 1.17 Applying solder paste to individual PCBs

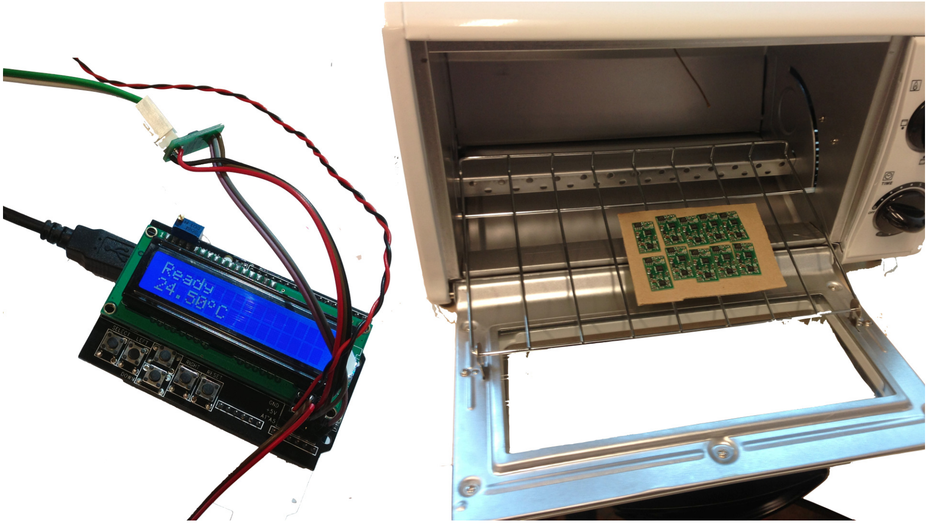


FIGURE 1.18 Converted toaster oven used for reflow soldering

accessibility are key ingredients in facilitating this upheaval in usage. It is interesting to realise how the tools shape the design process (and not only vice versa, i.e. that the design process can dictate the choice in tools).

Additive manufacturing (3D printing) has proved a technology with many benefits for the design process of mechatronics. The yielded design however is not immediately suitable for other production methods (CNC milling, injection moulding) since the printing process allows much design freedom than conventional tech-

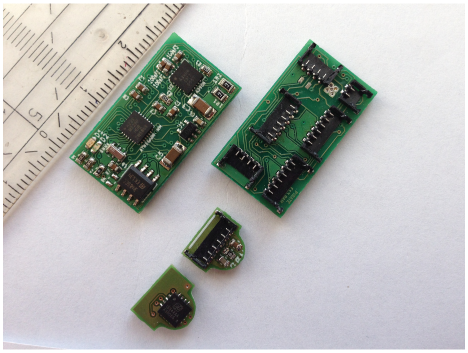


FIGURE 1.19 Motor drive board and the position sensor board

niques. Fortunately this might not be the problem it seems, since the available materials for 3D printers have seen a tremendous increase, as well as providers and services offering the tooling.

One of the major contributions to the *accessibility* of the tools listed in this chapter is the support by a large community of users, closely linked to various movements such as open-hardware, open source, FabLabs, MakerSpaces, HackerSpaces and other communities.

One of the major contributions to the *visibility* of the tools listed in this chapter is giving them a place directly in the space (the lab) where the design process takes place.

One of the major contributions to the *availability* of the tools is that they have not been installed to give a return in investment (money wise) regarding production costs, but that the machines are simply there, waiting for students, engineers and researchers to fill and fuel them with their ideas.

Many of the robot projects which are currently carried out are on the boundary between a laboratory prototype and an ‘industrialised’ robot for real use. The complexity of many of the proposed designs require production and manufacturing on an almost industrial scale, since in many situations only a complete robot can act as ’proof of principle’.

Fortunately the tools for digital (desktop scale) fabrication which have been popularised through the ‘maker’ world in recent years, allow ‘industrial’ manufacturing within the lab environment, and even go a step further by offering an unprecedented level of flexibility and agility in the design process.

Bibliography

[1] C. Anderson. *Makers, The New Industrial Revolution.* Crown Business, 2012.

[2] N. Bezzo, A. Mehta, C. Onal, and M. Tolley. Robot makers: The future of digital rapid design and fabrication of robots. *Robotics Automation Magazine, IEEE*, 22(4):27–36, Dec 2015.

[3] D. J. Borgerink. Development of the second pirate prototype using rapid prototyping. Master's thesis, Control Laboratory, Drienerlolaan 5, Enschede, 2012.

[4] E. Dertien, S. Stramigioli, and K. Pulles. Development of an inspection robot for small diameter gas distribution mains. In *Robotics and Automation (ICRA), 2011 IEEE International Conference on*, pages 5044–5049, 2011.

[5] E. Dertien. *Design of an inspection robot for small diameter gas distribution mains.* PhD thesis, University of Twente, Enschede, July 2014.

[6] E. Dertien. System specifications for pirate. Technical report, University of Twente, 2006.

[7] E. Dertien, M. Mozzafari Foumashi, K. Pulles, and S. Stramigioli. Design of a robot for in-pipe inspection using omnidirectional wheels and active stabilisation. In *IEEE International Conference on Robotica and Automation (ICRA) 2014*, 2014.

[8] N. Diolaiti, C. Melchiorri, and S. Stramigioli. Contact impedance estimation for robotic systems. *Robotics, IEEE Transactions on*, 21(5):925–935, Oct 2005.

[9] N.A. Gershenfeld. *Fab: The Coming Revolution on Your Desktop–from Personal Computers to Personal Fabrication.* Basic Books, 2005.

[10] V. Groenhuis and S. Stramigioli. Laser-cutting pneumatics. *Mechatronics, IEEE/ASME Transactions on*, PP(99):1–1, 2015.

[11] M. Imai. *Kaizen: The Key To Japan's Competitive Success.* Random House, 1986.

[12] A. Mader and E. Dertien. How to educate for creativity in creative technology. In Arthur Eger and Wouter Eggink, editors, *The 16th international conference on Engineering and Product Design Education (E&PDE2014)*, September 2014.

[13] C. Pulles, E. Dertien, H. J. van de Pol, and R. Nispeling. Pirate, the development of an autonomous gas distribution system inspection robot. In *International Gas union Research Conference, IGRC 2008, Paris, France*, USA, October 2008. Curan Associates.

[14] M. Resnick and E. Rosenbaum. Designing for tinkerability. In *Design, Make, Play: Growing the Next Design, Make, Play: Growing the Next Generation of STEM Innovators*, pages 163–180. Taylor and Francis, 2013.

[15] D. Schipper. *Mobile Autonomous Robot Twente*. PhD thesis, University of Twente, 2001.

[16] D. A. Schön. *The Reflective Practitioner - How Professionals Think in Action*. Basic Books, 1982.

[17] H. A. Simon. *The Sciences of the Artificial*. The MIT Press, 1996.

[18] S. Stramigioli and H. Bruyninckx. Geometry of dynamic and higher-order kinematic screws. In *Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on*, volume 4, pages 3344–3349 vol.4, 2001.

[19] J. J. G. Vennegoor op Nijhuis. Development of a pipe inspection robot. Master's thesis, Laboratory of Mechanical Automation and Mechatronics, University of Twente, 2007.

[20] W. G. Vincenti. *What Engineers Know and How They Know It*. Johns Hopkins, 1990.