Trends in Pneumatic Drives and Condition Monitoring Functions

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Abstract: Pneumatic drives are important parts in automation systems. This is based on its high performance especially for linear motion at low and competitive costs. Additionally pneumatic systems become more integrated, compact and increasingly more intelligent. The paper starts with a focus on the characteristics of pneumatic drives. It elaborates on additional customer benefits in case the full potential of this drive technology is used including effective maintenance and diagnostics. The strength of pneumatic drives is highlighted introducing some interesting applications.

Keywords: Pneumatics, pneumatic derives, mechatronic components, diagnostics, maintenance, pneumatic simulation,

1 Introduction

For many decades pneumatics is used and known as a robust and inexpensive drive technology. It has significantly helped the automation industry achieving its growth path. *Fig. 1* shows sales development in Germany representing with about 1.6 Billion Euros one third of Fluid Power. Compared to Hydraulics it has meanwhile achieved around 50 % of its sales. 20 years ago this was closer to 20% which stresses the importance of this driver technology. Next to automation we find high tech applications in tools, mobile and increasingly automobile comfort applications and in biomedical applications.

So which are the reasons for this continued and sustained growth? Looking beyond the surface we find a very innovative branch as the engine behind this success. Customer demands are taken serious and continuously challenge the companies. Next to product innovations we see the growing importance of services. Diagnostics and efficient maintenance is one example for this. Winning the competition with competing drive technologies also accelerates the pace for innovation.

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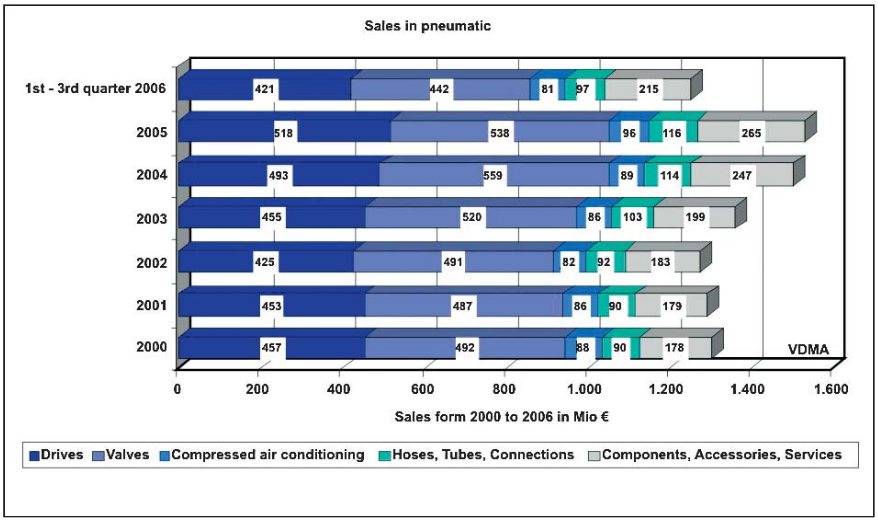

Figure 1. *Sales development of pneumatics*

2. Characteristics of pneumatic drives

In order to understand the driving factors for the strengths of pneumatics *Fig. 2* lists the characteristics of pneumatic drives. Robustness is a feature that allows its use in harsh industrial environments over long times.

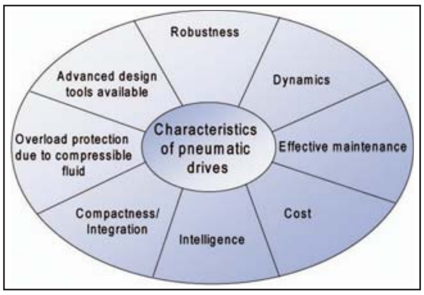

Figure 2. *Characteristics of pneumatic drives*

The compressibility is responsible for high dynamics based on the energy stored in the air but on the other hand it reduces efficiency of pneu-

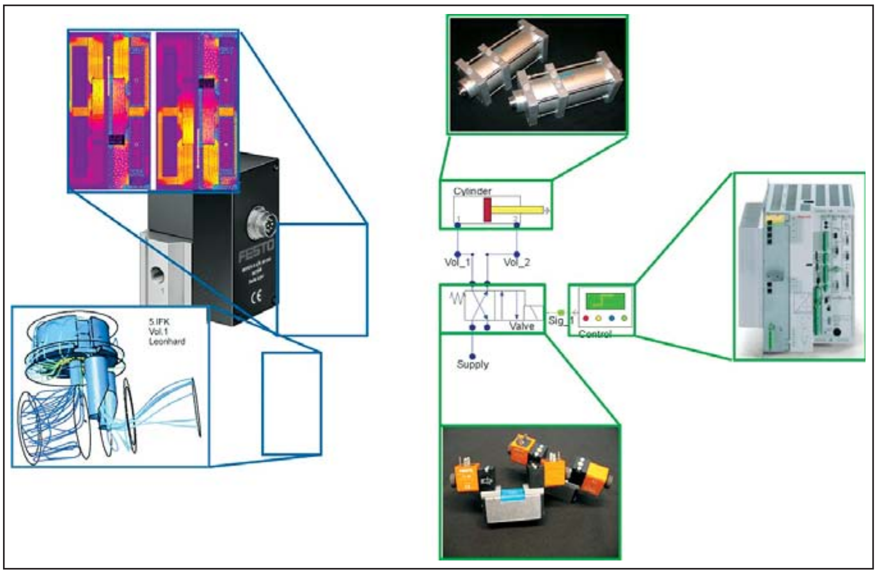

Figure 3. *Advanced design tools*

matic drives because usually no use of the compression energy can be made. Straightforward designs allow effective maintenance and keep costs down. Making use of developments in other disciplines such as electronics and sensors it becomes easy to design more integrated devices with increasing intelligence. Those integrated solutions with embedded intelligence are often referred to as mechatronics [6]. Powerful design tools are available today to back the design engineer. Some examples are displayed in *Fig. 3*. It is possible to simulate transient performance of solenoids using suitable FEM simulation tools /SCH06/. CFD simulations are readily available to find numerical solutions for flow and pressure fields within the pneumatic components [7]. These simulations allow deep insight into the physics explaining flow phenomena and allow flow optimization minimizing pressure losses. Dynamic simulation models help to design circuits and can reliably predict speeds and cycle times. [3].

In a research project conducted at IFAS together with VDMA and a project accompanying group of experts from industry the full potential of pneumatics was investigated [1]. The idea and results are presented in *Fig. 4*.

The upper part shows a standard circuit throttling the discharged air.

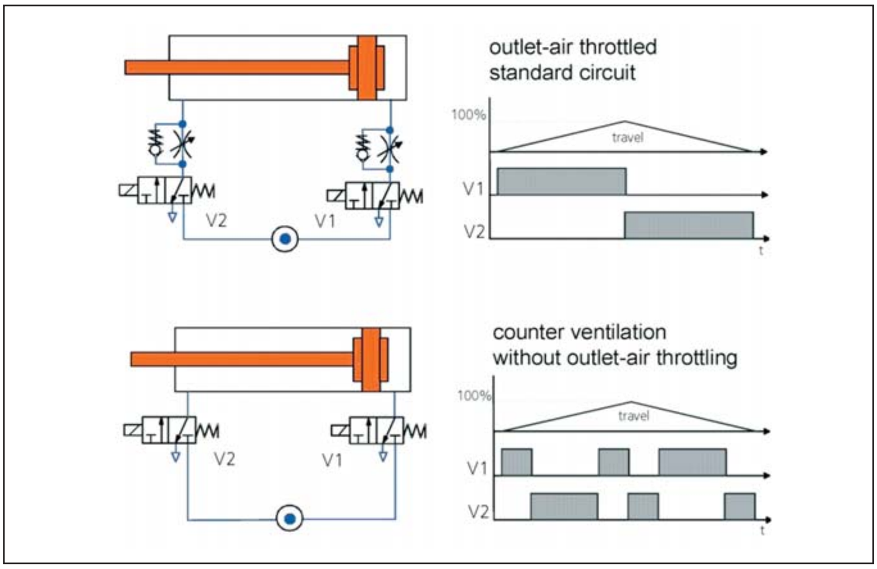

Figure 4. *Circuit for increased performance*

Valve 1 is open as long as the cylinder extends and valve 2 when it retracts. The circuit to use the full potential is depicted below. It doesn't use throttling valves and pressure losses only occur in tubes and the switching valves. The cylinder is vented with valve 1 on and achieves a very high speed. At a sufficient time before the cylinder extends valve 1 switches off and valve 2 on. Thus the rod side is vented and pressure builds up decelerating the cylinder. Shortly before the end position with damping is approached both valves switch in the opposite position pushing the cylinder in a controlled manner into the end position. It becomes clear that a good simulation tool is required to determine the switching points. Pressure, temperature, friction of cylinder and load, loads, displacement and valve as well as tube dimensions have a huge influence on the optimal switching times. Within the scope of the project experiments with parallel simulations were conducted delivering results presented in *Fig. 5*. For reasons of comparison stroke is chosen at 500 mm.

Compared to electric drives a huge advantage is visible for higher loads. Strength of the belt drive comes with very small loads and the conventionally controlled pneumatic drive performs better than the spindle

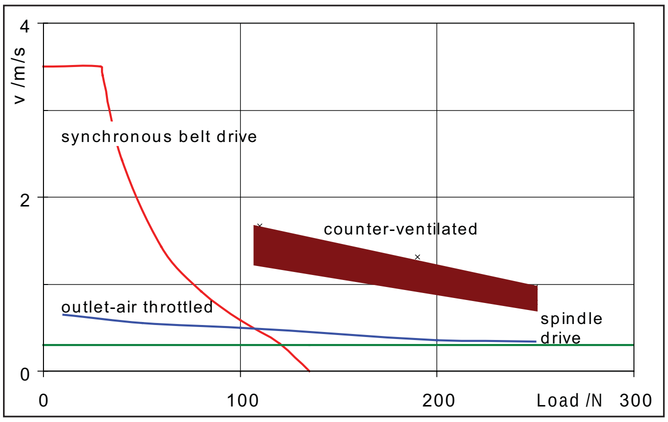

Figure 5. *Potential of pneumatic drives*

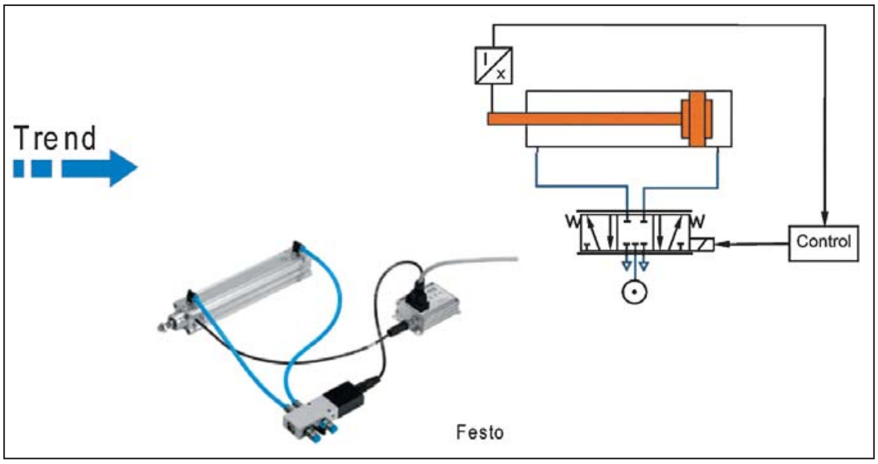

Figure 6. *Use of potential by Soft-Stop*

drive for all loads delivering more than twice the speed for low loads. 'The potential of the counter vented pneumatic drive is tremendous but very often unused in industrial applications. An industrial use derived from this idea is shown in *Fig. 6*. [12], www.festo.com. It is called Soft-Stop and has integrated sensors detecting when the

cylinder approaches the stroke ends. A closed loop displacement controller decelerates the cylinder "soft" into its end position(s).
Coming back to the characteristics integration and compactness. In *Fig. 7* some examples are displayed. With a high level of integration the following features can be achieved:

- decentralized intelligence
- compactness
- effective maintenance

In the upper part the steps from a single on/off valve to a valve island and finally to an valve island with integrated control function are shown. Below the same development can be seen from a cylinder to a drive with integrated valves and finally to an integrated drive with sensing and controlling capabilities.
Gaining from achievements in other disciplines helps the development of pneumatics, too. An overview of different structures to the field bus level is given in *Fig. 8*. On the lowest level we see actuators and typical examples of valves connected to those cylinders. Additionally we see some examples of sensors which are also integrated in some valve or actuator design. The highest level of integration is incorporated into valve islands with an integrated control function. All units on a lower and higher integrated level need to be connected to the pneumatic energy bus and the electronic field bus. Moving further up the hierarchy we arrive at the control centre responsible for the machine level and numerical machine controls and the factory level.

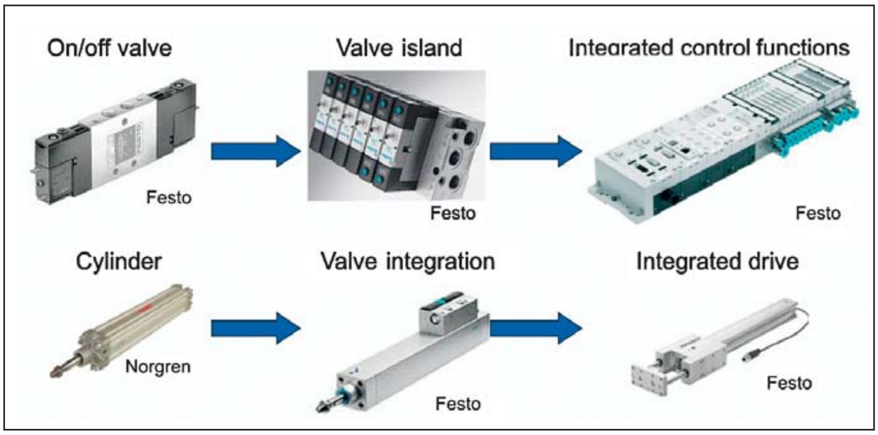

Figure 7. *Integration of additional functions*

A final characteristic of pneumatics which should be highlighted consists of its effective maintenance as presented in *Fig. 9* [12]. On the lowest level action will be taken after breakdown.

This leads to unanticipated brake downs and the production line is effected at an undesired time. In case maintenance happens at predetermined time intervals it might help to avoid unplanned production interruptions but costs are still higher compared to a condition based system. Modern

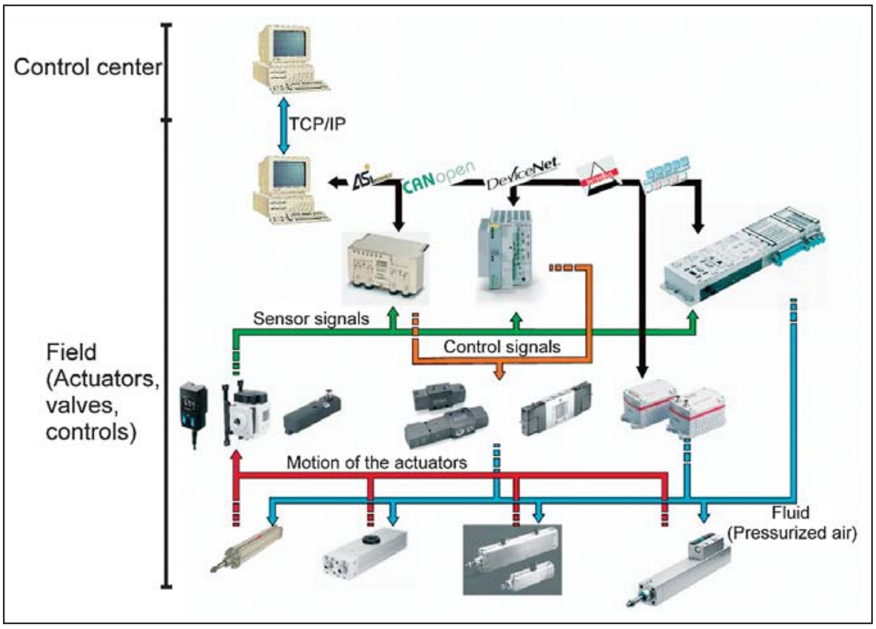

Figure 8. *Intelligence and field bus control*

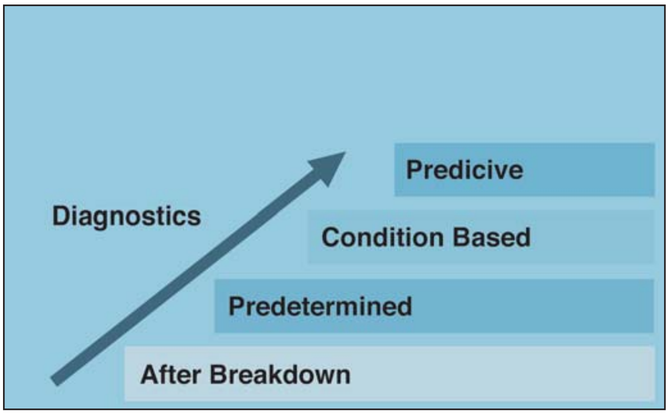

Figure 9. *Effective maintenance*

valve terminals offer all preconditions with their integrated electronics for effective local machine diagnostics. On the highest level this allows predictive maintenance. Integrated micro processors have free computing power for numerical routines and web servers are integrated offering additional IT services adding value to the customers processes and machines. The next chapter will go into some detail treating examples of diagnostics.

3. Applications and diagnostics

Diagnostics is important to avoid unplanned interruptions in product lines and to plan necessary maintenance work at times production is on hold for other reasons such as weekends, Holidays of after the last shift. Thus preventative maintenance is necessary and tools are required to predict the state of the process, the machine or its actuators and controls. As mentioned in chapter 2 we find and need computing power in the decentralized actuator and valve controls. This is highlighted in *Fig. 10* with the red signal lines. Independent of open or closed loop controls binary or continuous signals need to be processed in the embedded micro controller.

The idea is to use those signals available also for monitoring purposes [4]. In case no additional sensors are required costs are reduced to programming times and efforts. If production quantities are high to distribute the nonrecurring development costs the impact is minimal. Goal is to gain as much knowledge about wear, damage and defects without adding sensors which would increase the cost of condition monitoring. *Fig. 11* provides some insight into fundamentals and the means of diagnostics. The technical process provides a constant stream of data consisting of signals from switches or pressure sensors. Those signals can be used in different ways. On the right hand side a neural network is trained with typical failures and in the running process those can be detected as indicated with the different colours. Below the circuit for signal based condition monitoring is shown and in the lower left corner for model based monitoring.

circuit displays the welding cylinder and a balancing cylinder.
The welding cylinder is designed to perform the approaching stroke as well as the welding stroke. The balancing cylinder takes the weight out and allows floating while welding. This application is chosen in a common research project to detect friction, leakage and backlash [4]. The project is coordinated by VDMA in Frankfurt and accompanied by experts from industry. First results are promising and will be published shortly. *Fig. 13* shows the circuit of clamps also applied in the welding cell. The actuators are zoomed out for better visibility.

The harsh environment with short cycle times and heavy dust loads make this application an ideal candidate to implement and test condition monitoring methods.

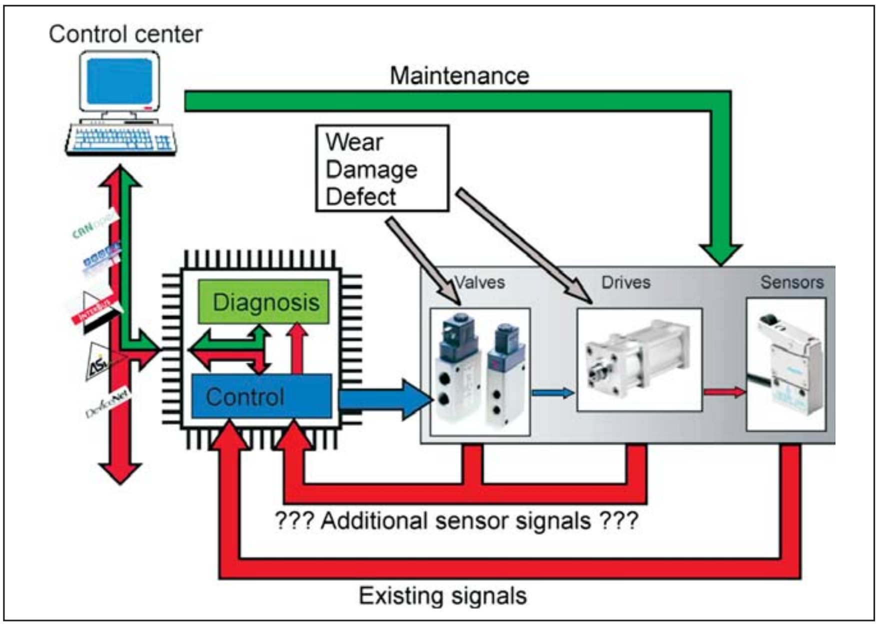

Figure 10. *Schematic of diagnostics*

It requires a mathematical model of the process or drive and instead of using additional sensors missing state variables are generated from the model.

The next figures will focus on some high end applications. The first example in *Fig. 12* displays the circuit and schematic of a welding gun, a zoom of the welding gun and its operation in a car manufacturing process. The

One diagnosis method, which is investigated at the Institute for Fluid Power Drives and Controls (IFAS), uses the time depend analysis of signals. This signal-based diagnosis method needs only the available signals to calculate faults states of an automated process. *Fig. 14* depicts the characteristics of the valve signals and the pressure sensors for a full operating cycle of a welding cylinder. Due to the clocked function of the welding control, the

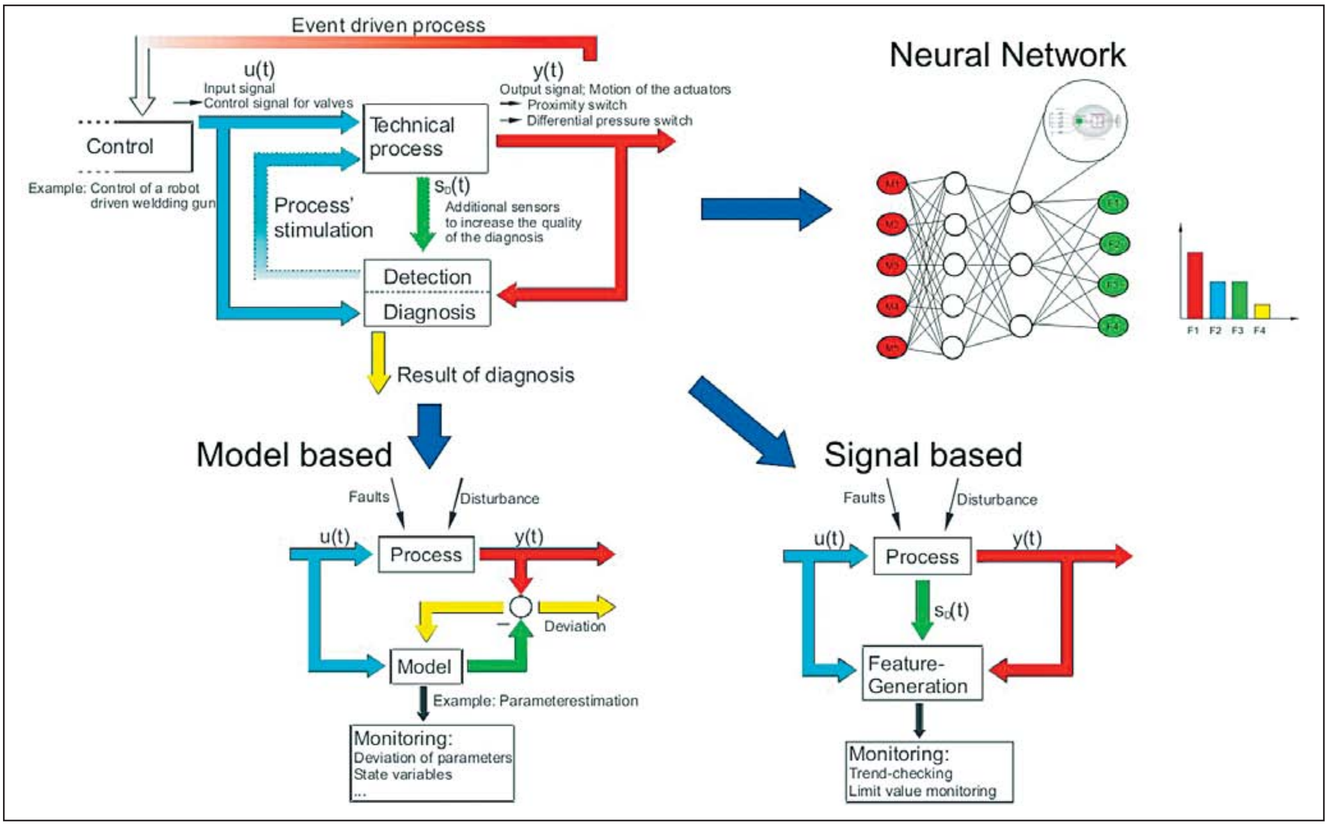

Figure 11. *Fundamentals and means of diagnostics*

signals are changing stepwise. First, a mathematical algorithm uses the signals to calculate so-called features. For example, the feature Δt_{Out} describes the time span of the valve signal initiating the cylinder's outgoing and the piston's arrival in the bedstop, indicated by the rising edge of the signal '*Welding pressure reached*'. Other features will be used to characterize the piston's ingoing time span or the pressure build-up in the cylinder's chambers. Sixteen features are extracted from the sensor signals and the valve steering commands during one welding cycle.

A method to classify the online calculated features to faults is given with so-called polynom-classifiers. This method has advantages due to the possibility to model complex featurefault relationships with respect to the order of the used polynoms. So, in a second step, well known feature-fault states have to be derivated from a valid simulation model of the welding gun or from measurements on a welding gun testrig to train the feature-fault matrix Ψ. The minimum number of well-known feature-fault states for training is based upon the order of the used polynoms.

Most common faults in welding gun applications are '*Internal Leakage*', '*External Leakage*' and '*Friction*'. So, the classification-function shown in

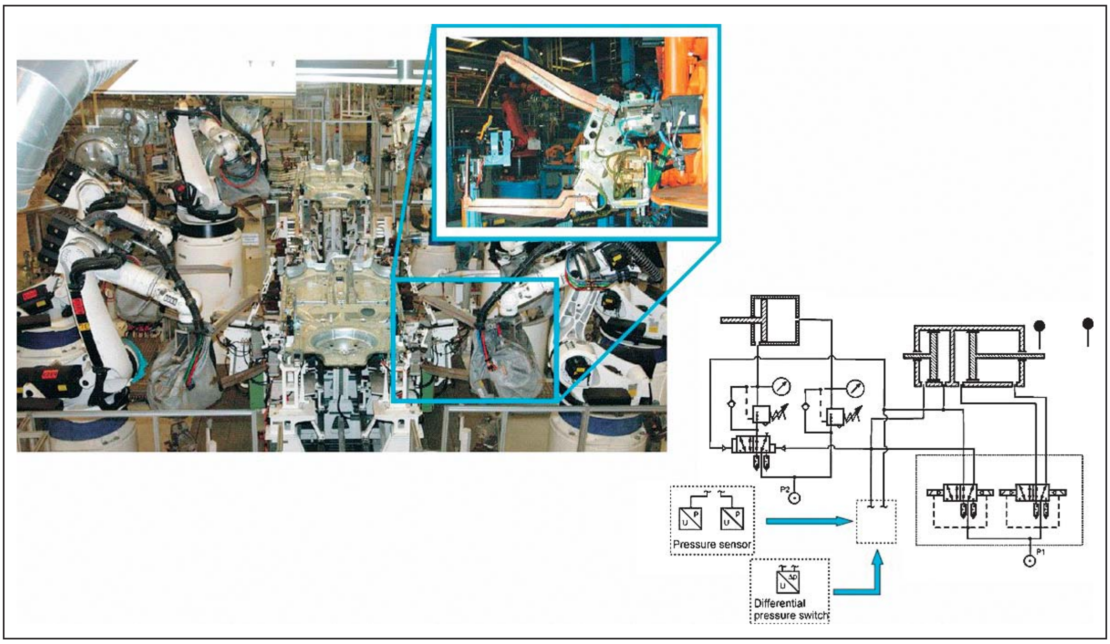

Figure 12. *Welding gun*

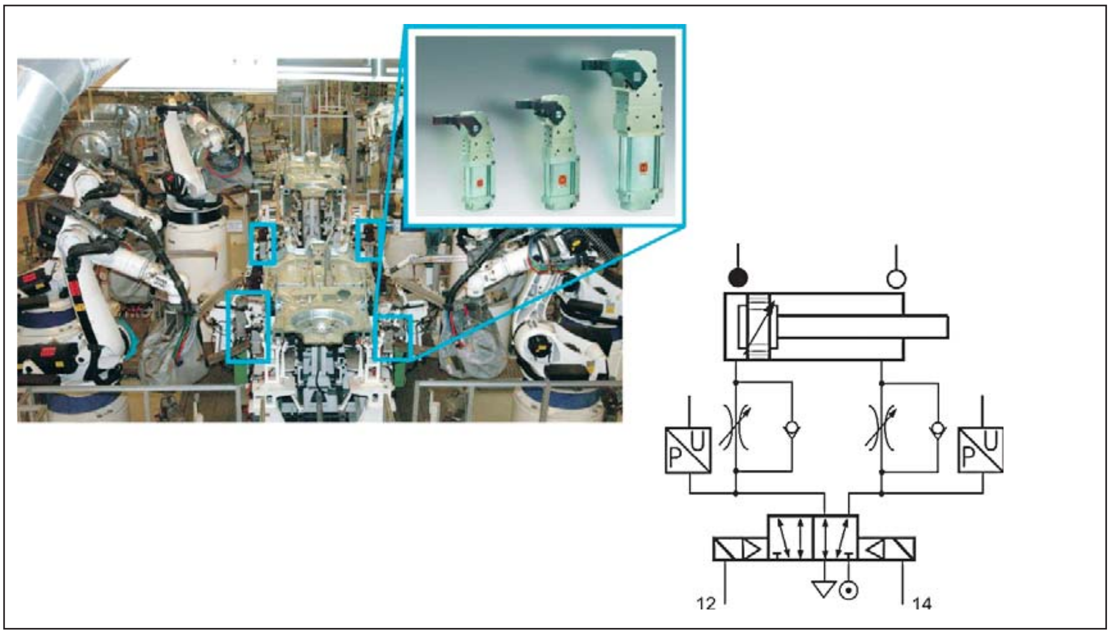

Figure 13. *Clamps applied in a welding cell*

Fig. 15 is designed to detect these forms of wear.

The following *Fig. 16* presents the results of the classification process via the polynom classifier for an additional load in form of *'Friction'* in the cylinder and the coupled mechanics. Additionally, *'External Leakage'*, *'Internal Leakage'* and *'Friction'* were brought in together. To get significant diagnosis result, the faults were activated stepwise. The process shown here consists of 20 welding points.

As can be seen, the detected fault follows the adjusted wear-phenomena in a satisfactory manner. Additionally, the method is able to differentiate between the different faults and provide the operator a permanent actualized characteristic of the system's health state. The overshoot during the rising edge of a failure is founded in a not fully adapted feature vector.

An interesting high tech application for pneumatics lies in mo-dern front end support for LCD production. During manufacture, very thin glass substrates need to be transported from one

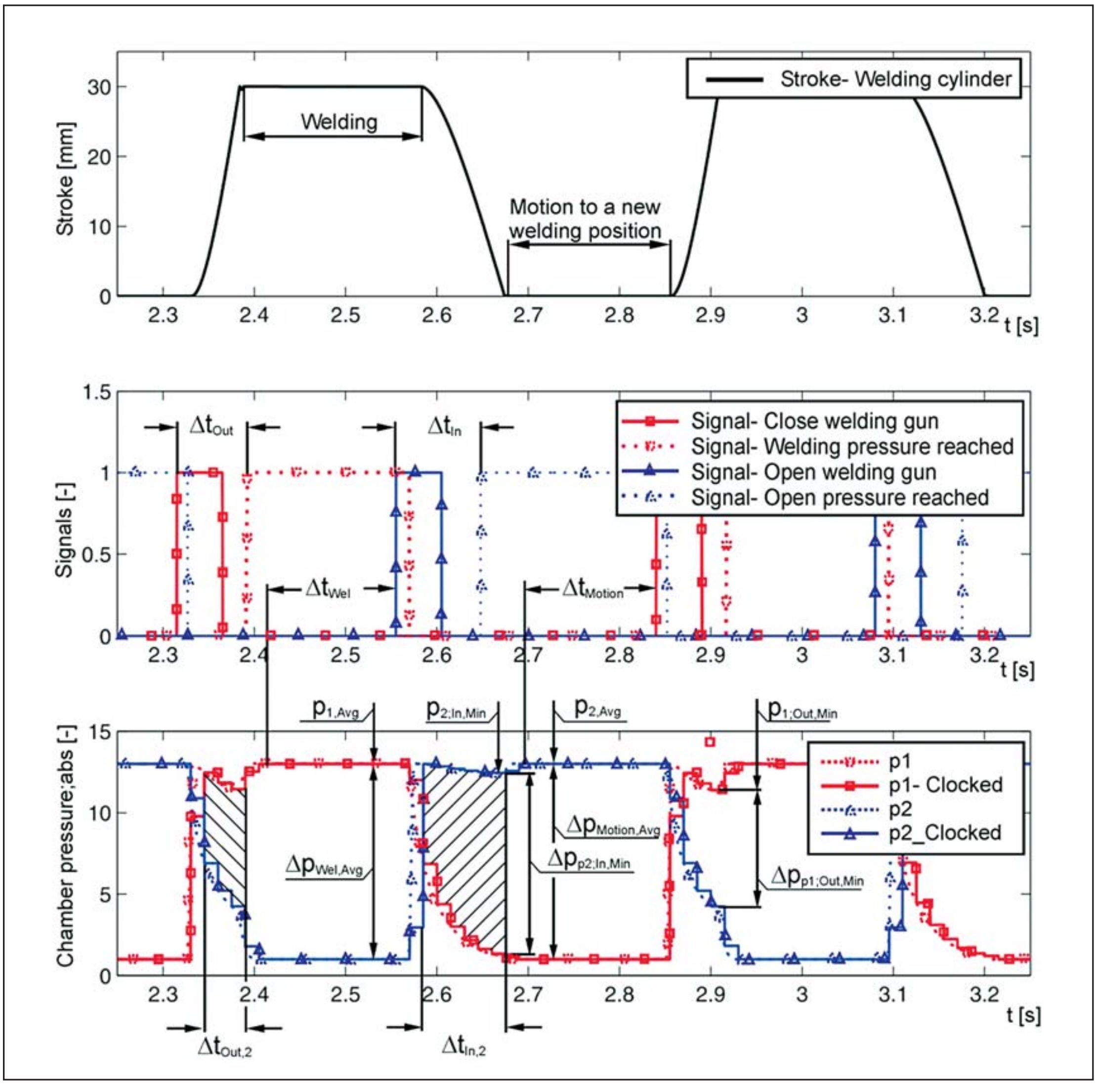

Figure 14. *Analysis of sensor and valve signals*

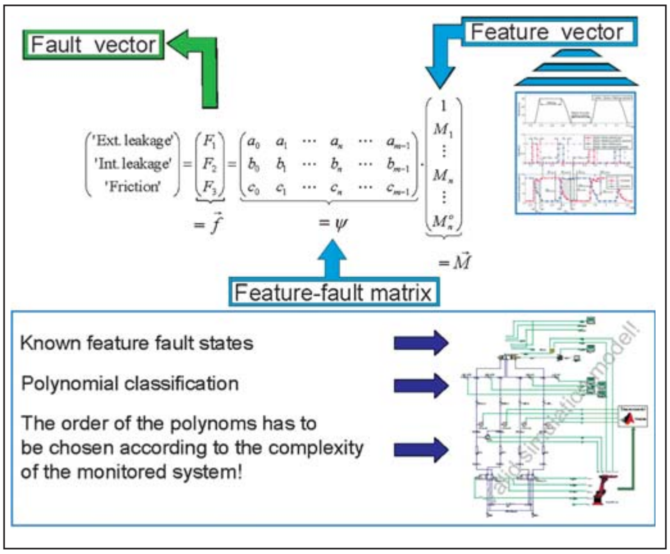

Figure 15. *Classification procedure*

working station to another. Using rollers driven by electric drives leaves skidmarks on the glass which have to be thoroughly removed as they could impair the following production steps. This renders the production process inefficient, as the multiple cleaning processes do not contribute to the panel's desired functionality. In order to provide a more efficient alternative, a pace drive for flat panels is developed at IFAS in a common research project together with Festo. The idea is shown in *Fig. 17*.

By holding the panel with a pneumatic gripping device, the pace drive can provide a reliable, skid free contact, and thus, reduces the requirement of additional cleaning between the production steps. In order to achieve a continuous movement of the panel, it is passed on from one pneumatic drive to the next.

Because of the drives' discontinuous movement, they have to be accelerated and decelerated periodically. Consequently, the drive's necessary stroke has to be chosen according to the maximum acceleration possible as well as the time spent during the handover process. *Fig. 18* shows the required drive stroke to reach a speed of 0.3 m/s against the acceleration and handover time.

In order for the pace drive to be competitive, it is necessary not only to provide better functionality, but also reduced operational cost compared to established conveyors based on electrically driven components. Pneumatic components have the advantage of being relatively inexpensive when purchased, but due to the low efficiency of the generation of compressed air, the lifetime costs have to be taken into account. Accordingly, it is of interest whether an optimised drive stroke exists that allows for a cost reduction. *Fig. 19* depicts the correlation between the drive stroke and operational cost per meter of transported substrate. For a conveyor speed of 0,3 m/s, a drive stroke of 1000 mm provides the lowest operational cost.

While the panel is passed on from one drive to the next, it is locked to two or more gripping devices on different drives at a time. To avoid skidding or misalignment of the panel, it has to be assured that all drives move at the same speed during this procedure. Consequently, a high accuracy of the pneumatic drives is necessary. However, the need for cost effectiveness demands a simple

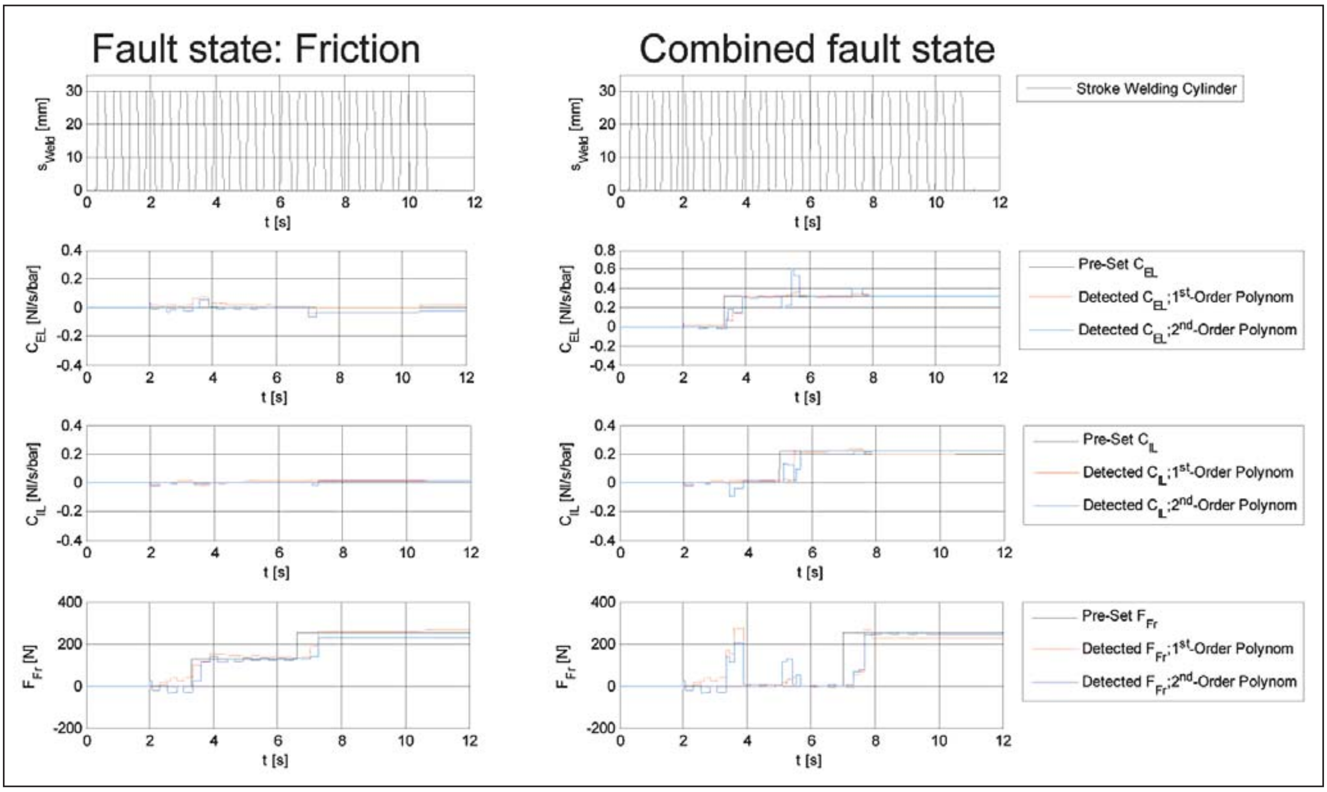

Figure 16. *Identification of fault state*

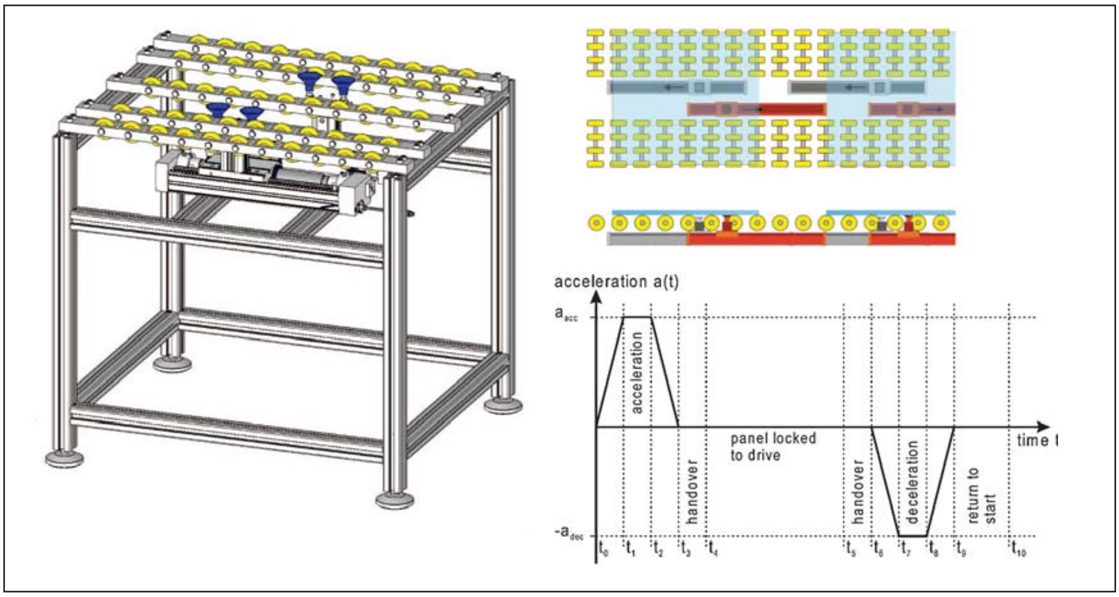

Figure 17. *Pace drive for flat panel LCD displays*

control strategy. An optimised feed forward control combined with a simple feedback control on the drives position and velocity is a promising alternative. *Fig. 20* shows a simplified diagram of the control design.

To facilitate the control while keeping good accuracy, a specialised valve, as shown in *Fig. 21*, is being developed. The valve features low gain around the desired operating point and thus provides high resolution, as well as high gain when high acceleration, but less accuracy, is required.

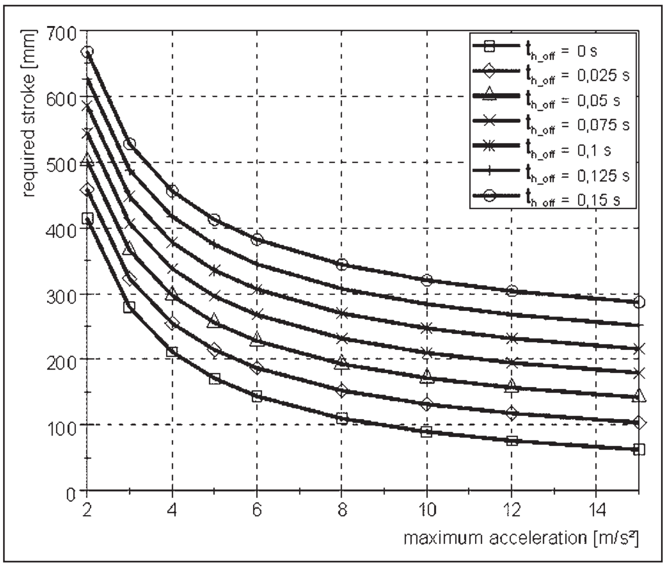

Figure 18. *Required drive stroke against acceleration*

First test results of the valve show that the intended characteristics featuring low gain for easy control of a constant speed and high gain for quick acceleration were achieved. As shown in *Fig. 22*, the valve features a fairly linear rise of the conductance with respect to the input voltage. At an input 2,5 Volts, the valve characteristics change towards a higher conductance gain, which is fairly linear as well until the conductance reaches a limit due to flow restrictions imposed by the pneumatic lines which connect the valve to the measuring equipment.

The advances of gripper development are displayed in *Fig. 23*. Following the arrows complexity, functionality and of course price are increasing. The vacuum gripper requires the lowest investment but energy costs need to be considered over the lifetime of the automation system.

The situation becomes even more important for the gripper using the Bernoulli effect. The advantage of this gripper lies in its ability being able to grip parts with holes. The on/off device depicted in the middle is more efficient exhibiting no continuous loss of air and can grip and clamp the parts. A flexible gripper developed by Gauchel [5] is able to clamp and position a part within a few centimetres. In this case one finger is in displacement control and the other in force control. The actuators need to exhibit low friction and the control algorithms have to address the specific requirements for sensible operations with this gripper. A gripper with three fingers is more universal and able to grip complex shaped parts [2].

The last applica-tion being introduced in *Fig. 24* shows a very interesting automation system not applied in industry but

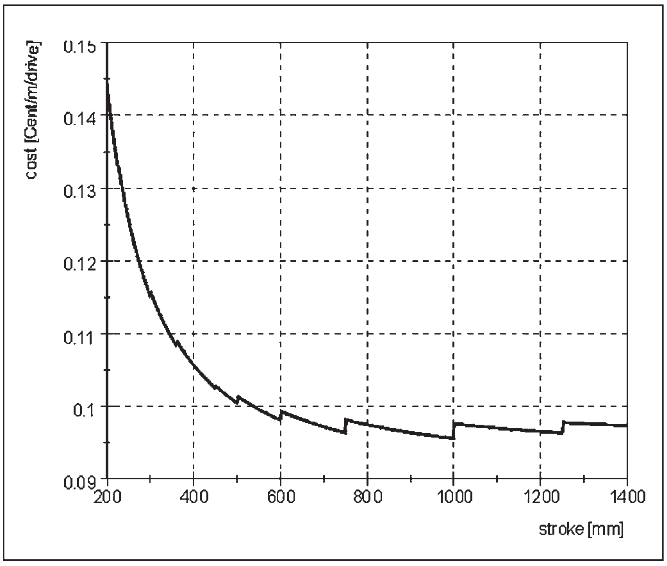

Figure 19. *Operational cost against drive stroke*

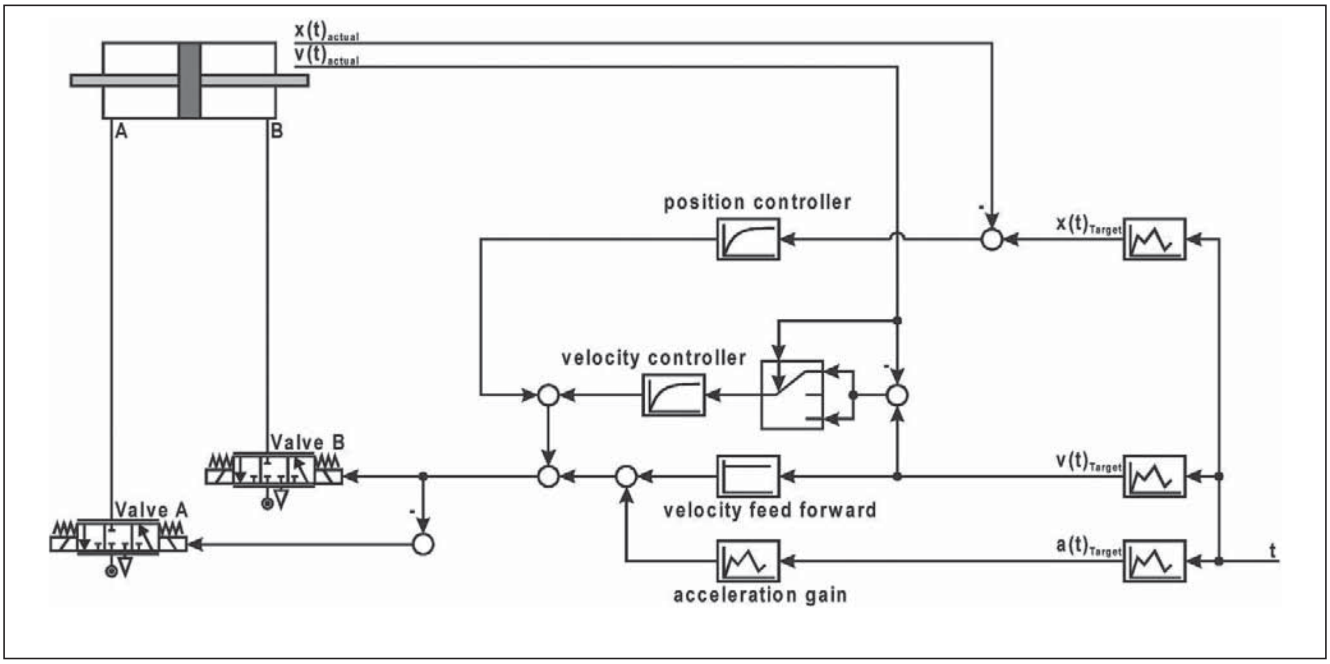

Figure 20. *Control design*

rather in the farming industry. It is an autonomous milking robot.

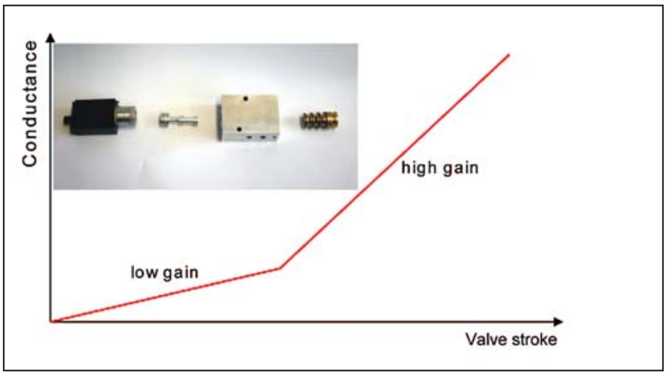

Figure 21. *Valve with optimised characteristics*

The servo-pneumatic drives have to scope with the harsh environment and need to function safely under all possible conditions. The limited stiffness of pneumatic drives becomes a major advantage in this application. Max. velocity is 0,3 m/s and max. acceleration 1,5 m/s^2. The required accuracy is specified to ± 2 mm. All drives incorporate fail safe behaviour.

The used platform is based on "plug and play" modules. Standard workpiece carriers on a planar table are used as drive systems and they are used to transport components to each processing station. These stations consist of handling modules with decentralized intelligence used for all the complex tasks necessary. It clearly shows the opportunities of fully integrated systems with on-board controller functionality used for control as well as condition monitoring [12].

4 Conclusions and outlook

Choosing the optimal drive for a given application is a continuing task for design engineer. In order to offer the customer and user of automation systems the best solution it is important to fully understand the characteristics of specific drives. For this reason the paper focuses on the characteristics of pneumatic drives explaining trends in academia and industry and how to make use of it. Condition monitoring becomes more important as unscheduled production down times are not tolerated and predictive action needs to be taken. Some examples demonstrate the importance.

The future for pneumatic drives looks bright in case the focus on the strength of pneumatics is pursued. Important

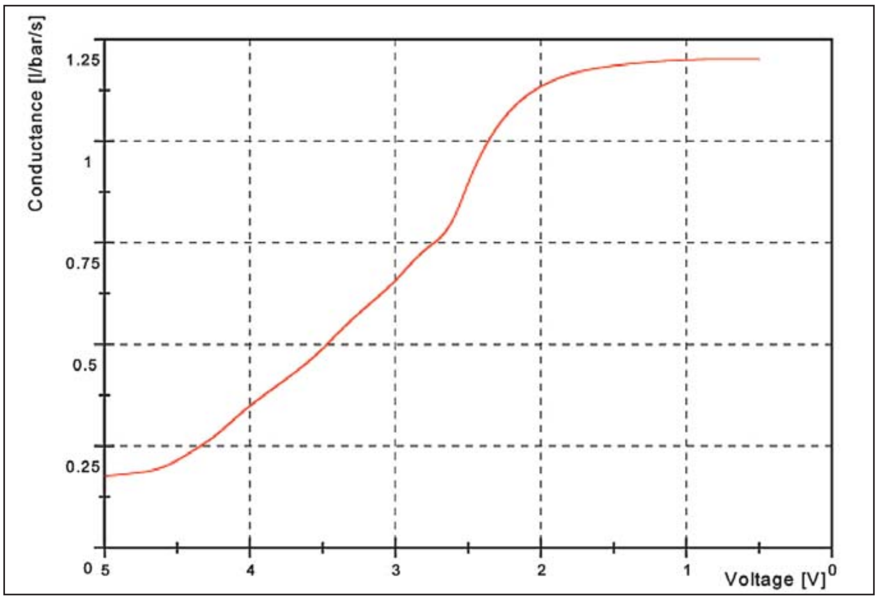

Figure 22. *Valve test results*

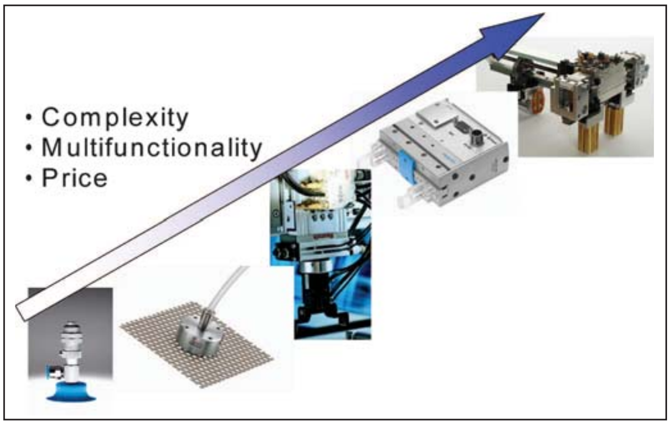

Figure 23. *Advances in gripper technology*

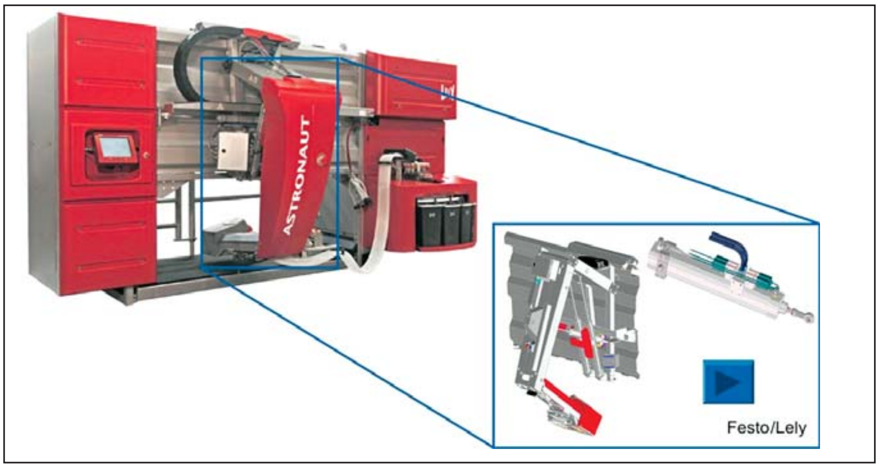

Figure 24. *Milking robot*

features are its robustness, flexibility, simplicity and controllability and maintainability. If it is possible to constantly satisfy customer demands with new innovations a long term success should be granted. Research and development performed in universities – educating young and talented engineers in this discipline – are an important mosaic on this path.

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Smer razvoja pnevmatičnih pogonov in nadzora delovanja

Razširjeni povzetek

Pnevmatični pogoni so še vedno pomembne komponente za avtomatizirane sisteme. Predvsem zaradi primernih lastnosti pri linearnih gibih, nizkih in konkurenčnih stroškov. Z razvojem so pnevmatični pogoni postali bolj integrirani, kompaktnejši in mnogo bolj inteligentni. Ïlanek uvodoma predstavlja značilnosti pnevmatičnih pogonov in v nadaljevanju prikaže bistvene prednosti in možnosti te pogonske tehnologije ob uporabi učinkovitega vzdrževanja in diagnostike. Prednosti in značilnosti pnevmatičnih pogonov so osvetljene z nekaj primeri.

Osnovne značilnosti pnevmatičnih pogonov so prikazane na *sliki 1*. Med njimi je treba izpostaviti robustnost, dinamične lastnosti, možnost enostavnega povezovanja z elektronskimi komponentami, razpoložljiva orodja za načrtovanje pogonov in inteligenco. Računalniško podprta orodja z možnostjo simulacije, ki jih imajo danes na voljo inženirji, omogočajo analizo obnašanja in izbiro ustreznih komponent. Tovrstne simulacije omogočajo optimizacijo toka in tlaka v pnevmatičnih komponentah, kar omogoča razvijanje krmilij in zanesljivo napoveduje hitrosti in čase delovnih ciklov (*slika 3*). Na osnovi raziskav strokovnjakov iz prakse in inštituta IFAS je nastala tudi rešitev na *sliki 4*, ki prikazuje običajno izvedbo dušenja obeh gibov in izvedbo s krmiljenim vklapljanjem 3/2-ventilov v zaporedju za dosego ustrezne hitrosti gibanja. Tako izveden pnevmatični pogon ima boljše lastnosti pri večjih obremenitvah, kar je bilo mogoče ugotoviti že s simulacijo pri načrtovanju (*slika 5*). Primer takega pogona je prikazan tudi na *sliki 6*, ki v povezavi s proporcionalnim ventilom omogoča še mehko zaustavitev.

Z integracijo krmilnih in pogonskih komponent pa je mogoče doseči razpršeno inteligenco, kompaktne konstrukcije in učinkovito vzdrževanje. Vzporedno z razvojem informatike in prenosa signalov se tudi v pnevmatičnih krmiljih vedno več uporablja večnivojska povezava krmilnih komponent preko mrežnih povezav in se ta uspešno povezujejo v krmilje numerično krmiljenih strojev.

Opazen je tudi razvoj na področju vzdrževanja, kjer se poskuša s predvidevanji izključiti prekinitev delovanja pnevmatičnih pogonov. Moderna krmilja z vgrajeno elektroniko omogočajo učinkovito diagnosticiranje in predvidevanje zastojev na nivoju strojev, na višjem nivoju pa je preko mrežnih povezav mogoče servisiranje krmilij pri kupcih.

Diagnostika je nujna za izogibanje zaustavitvam, ki niso bile načrtovane, in za načrtovanje potrebnega vzdrževanja. Takšno preventivno vzdrževanje je nujno. Ideja sodobnega vzdrževalnega sistema je uporaba že obstoječih senzorjev. Cilj je vsekakor pridobiti čim več znanja o obrabi, poškodbah in napakah brez dodatnih senzorjev, kajti ti podražijo nadzorovanje delovanja sistema. Potrebna je integracija več znanja (matematičnih modelov in odločitvenih metod) za uporabo in obdelavo informacij, ki jih dajejo senzorji. Tako je na primer bila narejena raziskava o možnosti nadzora delovanja varilne celice. Težki delovni pogoji so kot nalašč za uporabo sistema nadzora. Kot vir informacij je bil upoštevan potek gibanja batnice cilindra (*slika 14*). Izdelana sta bila ustrezen matematični model in simulacija, ki dasta dovolj dobre informacije o notranjem in zunanjem puščanju ter trenju.

Pnevmatične pogone in njihovo uporabo je potrebno oceniti s stališča stroškov in prednosti, ki jih nudijo. Tak primer je prikazan na *sliki 17*, kjer je za premikanje plošč uporabljen pnevmatični pogon z vakuumskimi prijemali. Sistem uspešno izpolnjuje zahteve natančnosti (krmilje) in hitrosti oziroma pospeševanja. Za visoke zahteve pri natančnosti pozicioniranja je bil razvit poseben ventil, katerega karakteristike so prikazane na *sliki 21*.
Pnevmatični pogoni pa se lahko uspešno uporabljajo tudi pri avtomatizaciji v kmetijstvu. Značilnost pnevmatike, elastičnost pogona, se lahko uspešno uporabi za posebne zahteve, ki so pojavijo na primer pri molži.

Zaključiti je mogoče, da bodo pnevmatični pogoni tudi v prihodnosti zadovoljevali uporabnike s svojimi značilnimi prednostmi. Inovacije na področju pnevmatike bodo omogočile snovanje naprav po željah naročnikov in z ustrezno diagnostiko tudi uspešno uporabo.

Ključne besede: pnevmatika, pnevmatični pogoni, mehatronske komponente, diagnostika, vzdrževanje, simulacija v pnevmatiki,