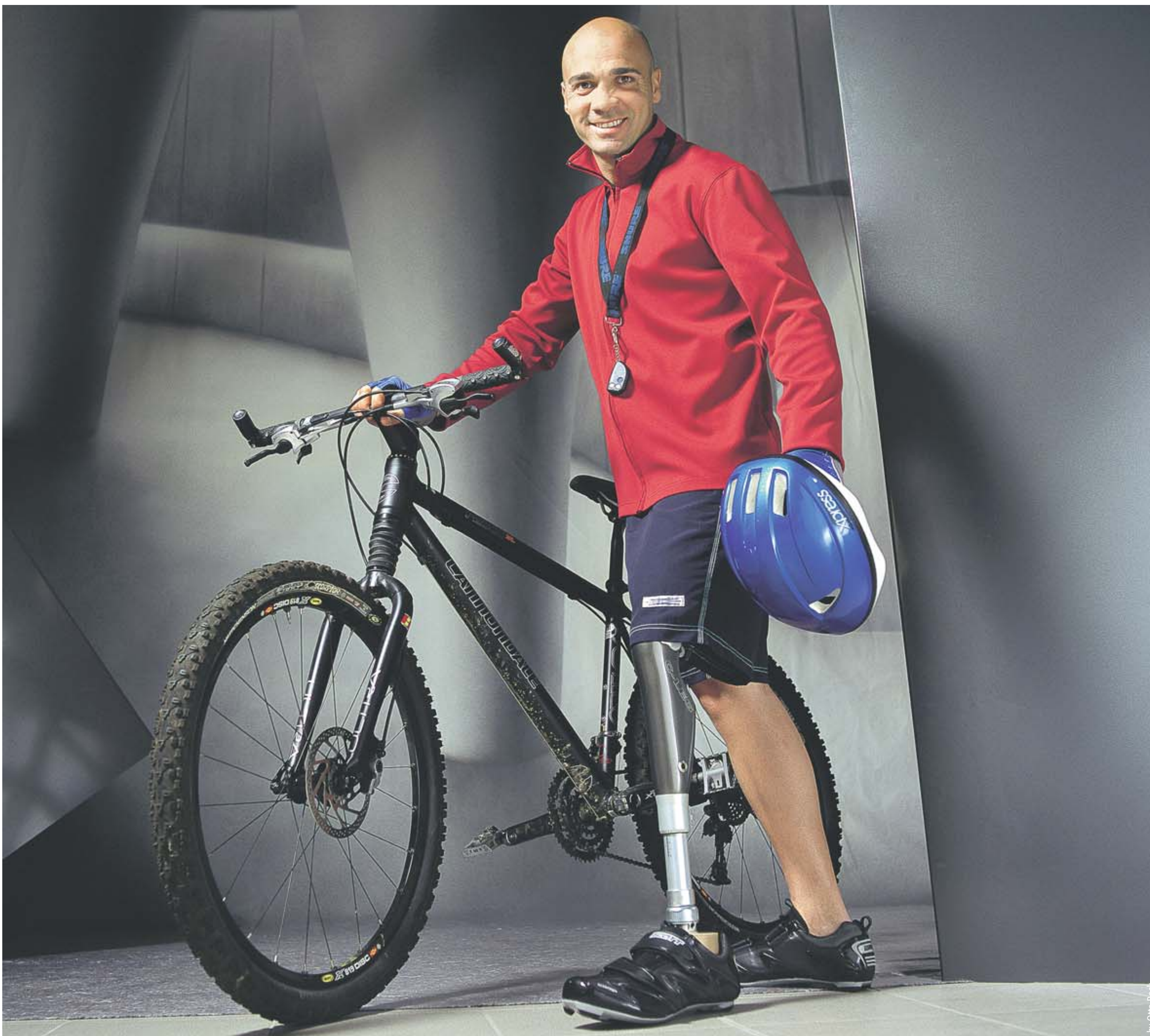
Health care: Matrix Controller for simple, accurate control of non-constant, cyclic set profiles

Complex control technology, simple implementation

Matrix Controller is the universal controller algorithm from Otto Bock HealthCare GmbH that was primarily developed for a machine that tests prosthetic feet. However, it is also suitable for pneumatic servo positioning of the type which occurs in robot technology or when monitoring cyclic, non-constant process sequences in CNC machines and when controlling non-constant processes in drive technology, for example. The Matrix Controller was built with PC-based control technology from Beckhoff. The controller algorithm was programmed in IEC 61131 and implemented directly in TwinCAT PLC. The aim of this development was a software-based solution that enables the use of standardized hardware.



Prosthetics user with the world's first microprocessor-controlled knee joint, C leg from Otto Bock HealthCare

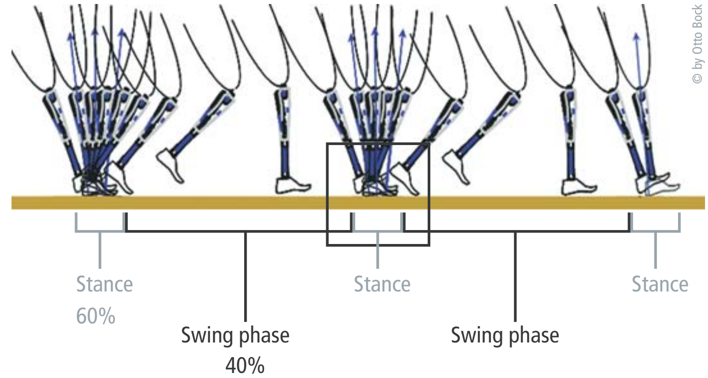


Diagram 1: Stance and swing phases of human walking

Otto Bock Healthcare, the MedTech company based in Duderstadt, Germany, manufactures products for people with physical disabilities and limited physical mobility. It has a wide range of products, from prosthetics, wheel chairs and rehabilitation aids including orthopedic splints/braces. The company, which is owned and managed by the third generation of the Bock family, can look back on a 90-year success story founded on innovative drive and an early international focus. The Otto Bock company holds the property rights for 670 granted and 524 registered patents in total.

Prosthetic feet fulfill more than just a cosmetic purpose. Depending on the type of patient and whether he or she has age-related limitations or is a highly active amputee, these aids support the entire process during walking and standing. Testing machines, which repeat the standardized stress and angle profiles during the stance phase (diagram 1) evenly two million times, are needed for performing standardized tests on newly developed prosthetic feet according to ISO standards. The aim is to bring components for prosthetics onto the market that are contemporary, highly functional and reliable over a long time.

This kind of testing machine is equipped with a standard pneumatic cylinder with two proportional valves, an AX2010 Beckhoff Servo Drive with EtherCAT interface, an AM277S Beckhoff servomotor and planetary gear unit with a power of 4.5 kW, various power and position sensors as well as TwinCAT PLC software running on a Beckhoff Industrial PC (diagram 2). The IPC controls up to four test modules simultaneously via EtherCAT. The problem: the combination of a prosthetic foot and pneumatic cylinder produces a complex interaction which constantly changes throughout the simulated stance phase and is also influenced by both the type of foot construction as well as its size and wear in the testing machine. The prosthetic foot reacts differently to stresses with every rolling motion.

Testing machine for prosthetic foot

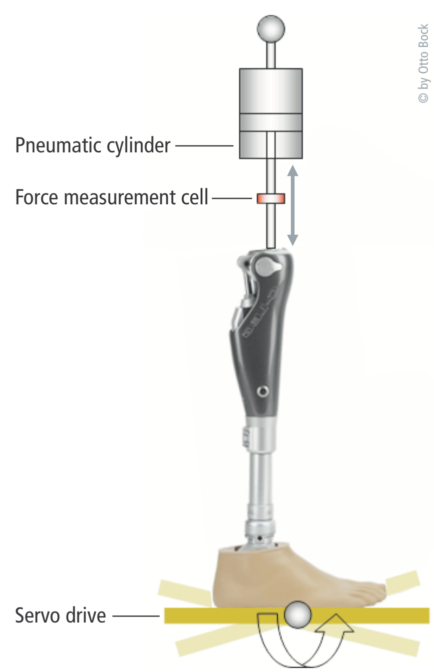


Diagram 2: Simulation of ground reaction force

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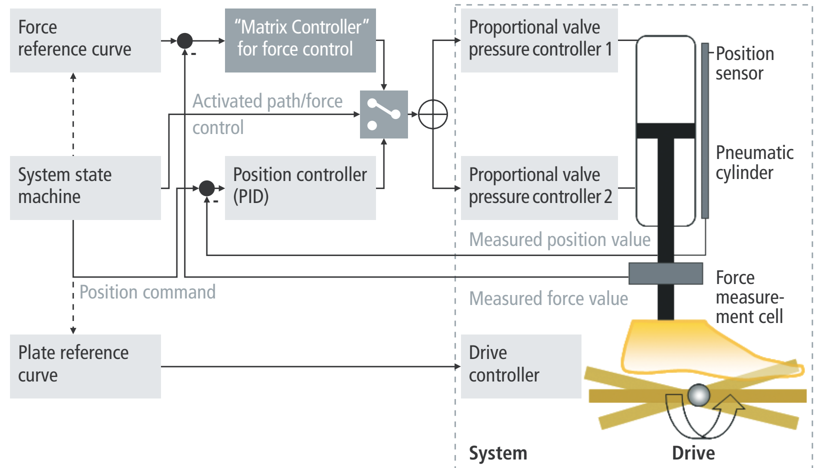

Diagram 3: Diagram of system design

System design

The servo drive chosen for the foot plate controls the foot position with the necessary precision even under considerable stress. The pneumatic system is controlled via two proportional pressure valves according to the direction in which the piston moves. In this way, the force can be controlled in both directions (up/down) and controlled via the air introduced. The system is controlled via the PLC with a cycle time of 5 ms (200 Hz). A walking cycle lasts 1 s (1 Hz). The foot position is crucial for the measurement. For this reason, a PID position controller is used at the end of the stance phase when the force controller is no longer active. The state machine decides when the position controller or the force controller is activated (diagram 3).

System analysis

In order to examine the system responses, the force progression was regulated by the valve controllers. In the process, the position controller and the force controller were used, the former in closed control loop and the latter in open control loop. In this mode, however, the desired force progression curves did not tally with the actual ones (diagram 4).

The obvious phase shift was the result of the PLC cycle time, the delay caused by the fieldbus, the dead centers of the valve controller, the low-pass behavior of the pneumatic cylinder and the system response time of the foot. In order to eliminate this phase shift, the output signal was shifted by means of a FIFO buffer to 18°/Hz (18° at 1 Hz test cycle), depending on the test speed.
Although the difference in amplitude was minimized, it was not entirely removed (diagram 5). An additional force error had to be compensated. At every angle of the foot, the amplitude deviates from the set value by a different amount according to the system characteristics of the prosthetic foot.

The Matrix Controller

Using a PID controller with different parameterization for each point of the curve did not produce a stable signal. Since the foot system also changes with each angle of the plate, a separate PID controller was used for each plate angle.
The stance phase is produced with a cycle frequency of 1 Hz and a PLC cycle time of 5 ms with 120 PID controllers. The remaining cycle time is

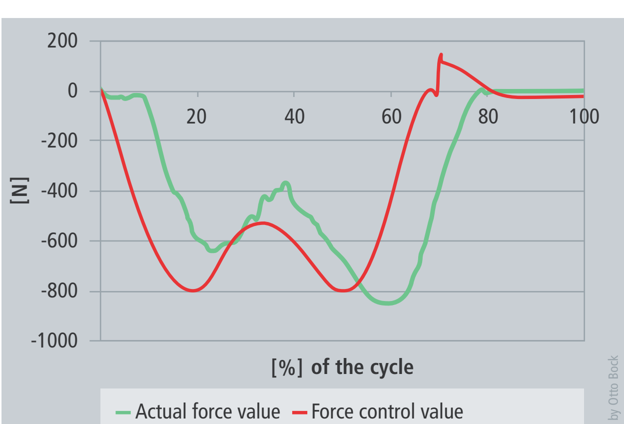

Diagram 4: System reaction in open-loop control operation

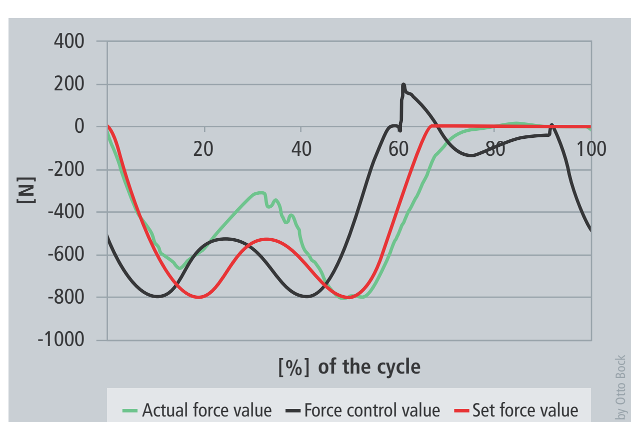

Diagram 5: Minimizing the phase shift

Advantages of the Matrix Controller

- The Matrix Controller can control systems which give different step responses at different times within a control cycle.
- The parameterization of standard controllers requires no specific controllers or system models. This makes it possible to adapt the control cycles to individual customers' needs quickly and at relatively little cost (e. g. for special test cycles in testing machines, with filling processes as well as hydraulic and pneumatic control processes).
- Adaptive controllers, adaptive PID controllers, fuzzy controllers, complicated system models or expensive controllers are no longer needed because the sampling rates can remain very low.
- The Matrix Controller system already works with extremely long cycles (5 ms, sampling rate 200 Hz) and needs only a small amount of computing power.
- The system is then corrected accurately within a very narrow set value corridor. When the Matrix Controller was used in testing machines for prosthetic feet the precision of the pneumatic actuators was increased five-fold.

needed for repositioning the prosthetic foot. Each PID controller works in its area of the total curve. Information from the last test series is used to correct the force errors in every point. The standard PID algorithm consists of functions for the proportional (Kv), integral (Tn) and differential (Tv) area. These can deviate from one another from controller to controller.

Together they produce the PID parameter matrix:

$$M = \begin{pmatrix} K_{R0} & K_{R1} & \dots & K_{Rn} \\ T_{N0} & T_{N1} & \dots & T_{Nn} \\ T_{v0} & T_{v1} & \dots & T_{vn} \end{pmatrix}$$

Changing the parameters of each individual controller makes it possible to justify the controller output for each area of the curves separately.

A five-fold increase in precision

This simple method for controlling the force profile produced an immediate improvement. Diagram 6 shows the behavior of the system after only 200 test cycles. There is only approx. 3 percent deviation with two million stress cycles. While the controller matrix works in cycles, the output signal can be displaced by 18° to compensate the dead center and the system-related delays.

As long as the feedback signal is located within a defined curve tolerance, the Matrix Controller will not intervene. If the force progression changes within the two million stress cycles because the prosthetic foot wears out, the Matrix Controller will control up to a specified number of correction settings subsequently. If this number is exceeded, the prosthetic foot has not passed the test. The measured data facilitate the analysis of possible design faults or production weaknesses.

The Matrix Controller is easy to implement and manages systems with complex control requirements. For this it needs only the computing power of a single PID controller for the PLC cycle. "A cycle time of 5 ms (200 Hz)," Erik Albrecht-Laatsch explains, "proved sufficient to regulate the pneumatic control. Neither simulations nor other complex technologies were needed to control the system."

Patented Matrix Controller has many uses

Controlling cyclic occurrences with non-constant processes places considerable demands on control technology. The Matrix Controller introduced here offers a surprisingly simple solution: The non-constant control profiles are divided into many constant control sections. This produces a time-control matrix in which each matrix column is represented in two ways: the short time section of a non-constant set profile is process-related; the autonomous, constant set profile is segment-related. Traditional PID controllers can be used to control the process within this section. This innovative approach illustrates a new model in control technology for all types of non-constant and constant periodic signal profiles. For a license holder, the patented Matrix Controller (EP 1 982240B1) is effective, safe and relatively inexpensive to use in many other contexts as well, such as testing machines, robots, CNC machines and when controlling positioning and force for other pneumatic and hydraulic applications.

Otto Bock HealthCare GmbH **www.ottobock.de**

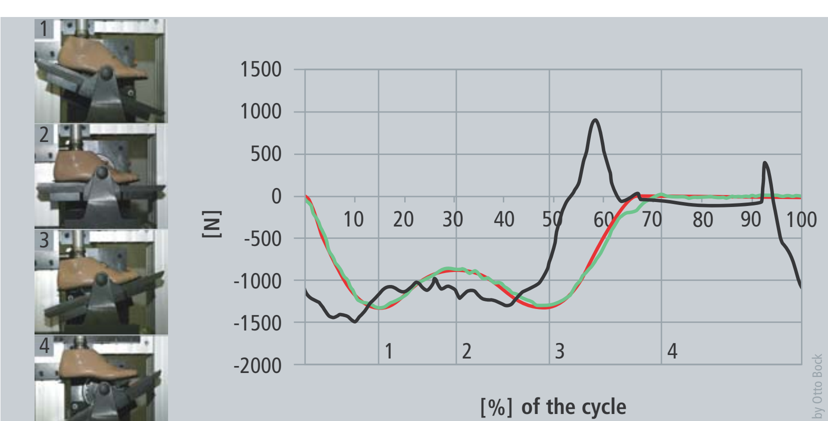

Diagram 6: Reference curve (red), feedback curve (green) and controller output curve (black)