Improved Machine Performance With Feedforward Control

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Machine control using feedforward (FF) can enhance the positioning and tracking substantially. The size of the systems is not important. Whether you are working with a microsystem or a steel rolling mill, feedforward control offers enormous possibilities. A practical example is a project that was carried out at the Maritime Research Institute Netherlands (Marin). The company Controllab Product B.V. has implemented feedforward control on one of the towing tanks of the Maritime Institute and substantially reduced the tracking error.

Marin

The Maritime Research Institute the Netherlands (Marin) tests the seaworthiness of new ships and offshore constructions. To carry out these tests, the Marin has a number of basins in which these ships, scaled down of course, can be tested. These tests are obliged by international classification offices such as Lloyd's. Fine examples are the sailing yachts ABN-AMRO 1 and 2 that won the Volvo Ocean Regatta in 2006. These ocean racers have been tested in the basins of the Marin. The largest basin of the Marin is the Seakeeping & Manoeuvring Basin. This basin measures 170 meters by 37.5 meters. On two sides 60 centimeter wide flaps are mounted for wave generation. Any desired type of wave can be generated with a maximum wave height of 0.45m. The Seakeeping & Manoeuvring Basin is applied with a carriage which can run along the entire length of the basin. The carriage consists of a mainframe that spans the width of the basin and a subframe mounted to the mainframe. The carriage can follow all ship movements in the horizontal plane. A platform is attached to the subframe. The platform carries measurement equipment and computers for the analysis of measurement data. The platform has space for several operators to control the carriage and the ship model.

Problem

The Seakeeping & Manoeuvring Basin is frequently used for free running trials. In these trials a ship will run independently through the basin. At every trial there is a cable between the ship and the carriage. This cable carries the sensor data, the steering commands and the energy supply. The cable should never be stretched to prevent the carriage towing the ship and thus disturbing the free run. This means that the carriage should follow the ship very accurately. Until recently the carriage was equipped with a traditional feed-back controller. A problem of this controller was the slow response. This prevented the Marin doing trials with fast moving ships such as models with water jets. Therefore the Marin commissioned Controllab to extend the controller with a feedforward loop to improve the response speed. The implementation and testing of the adapted controller can only be performed during regular maintenance with a maximum time slot of 16 hours.

Feedback

What is feedforward control? To explain the working principle of this type of control, a short explanation of control is necessary. We will do this using a random electric machine. The input is the motor torque and the output is the machine position. The most common method of control for such a machine consists of a feedback loop with a PID controller. The PID controller tries to find a motor torque that will drive the error (E) between the desired position (SP) and the actual machine position (Y) to zero. Refer Figure 1.

Feedback controllers can only act if there is an error between the desired and measure position. The error is minimal when the machine is stopped at a fixed position but will increase if the machine starts to move.

Feedforward

Feedforward controllers do not suffer from slow response. Feedforward controllers have a direct link between the desired position (SP) and motor torque. Perfect tracking of the machine (y = SP) is obtained when the feedforward is an exact inverse of the machine. The feedforward controller will then yield exactly the right motor torque that is needed to make the machine position (Y) equal to the desired set point (SP), as shown in Figure 2.

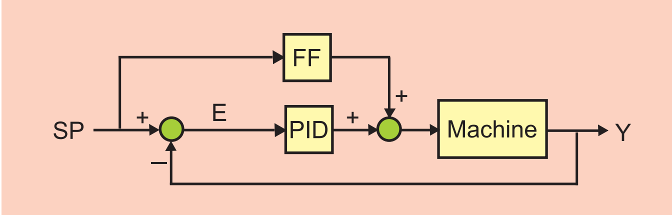

Figure 2: Feedforward control combined with feedback control.

In practice it is impossible to make a perfect inverse machine. That is why feedback control is usually added to a feedforward controller to reduce the remaining error (E). Even for an imperfect feedforward controller this error will be substantially smaller than with feedback control only. In most cases existing feedback controllers can be extended with a feedforward controller. This requires substantial knowledge of the machine, because the inverse machine is needed for the feedforward loop.

Carriage

Back to the Seakeeping & Manoeuvring Basin. To follow ships, the carriage is equipped with a stereo camera system that can measure the ship position with an accuracy of 0.1 mm in an area of 2 by 2 meters, as shown in Figure 3.

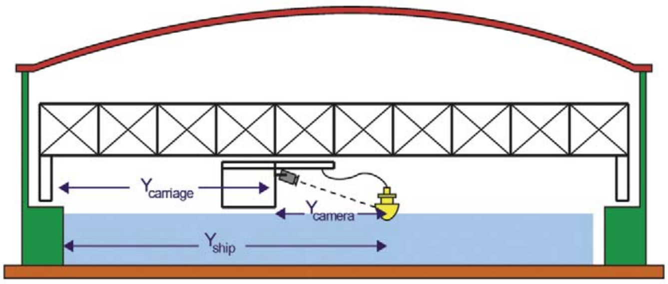

Figure 3: Camera system to measure the ship position.

The camera position is equal to the ship position minus the carriage position and thus equals the position error. The traditional control loop consists of a PID controller, that translated this position error into a velocity signal that is sent to the motor controllers. The motor controllers drive the motors which are connected to the carriage wheels.

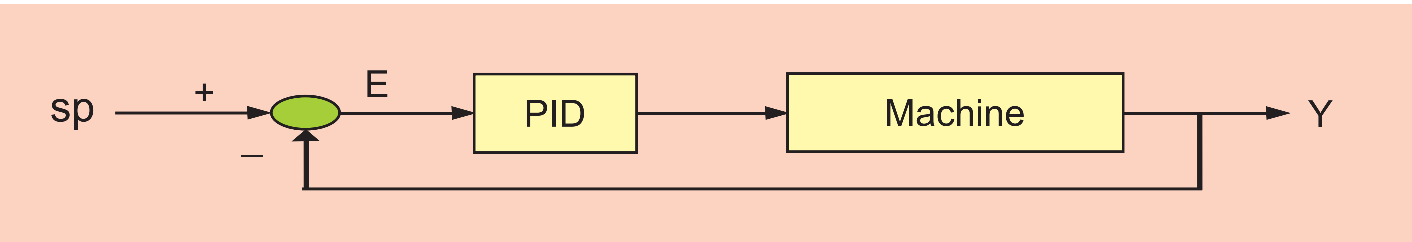

Figure 1: Traditional feedback loop with PID control.

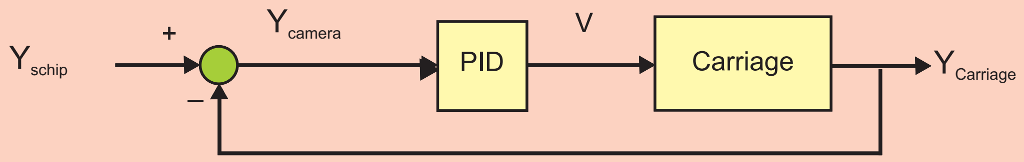

Figure 4: The traditional PID controller translates a position error into a velocity signal for the motor controllers.

The traditional control loop, as shown in Fig. 4, can easily be extended with feedforward control. The feedforward controller translates the measured ship position into a velocity signal for the motor controllers, as shown in Fig. 5.

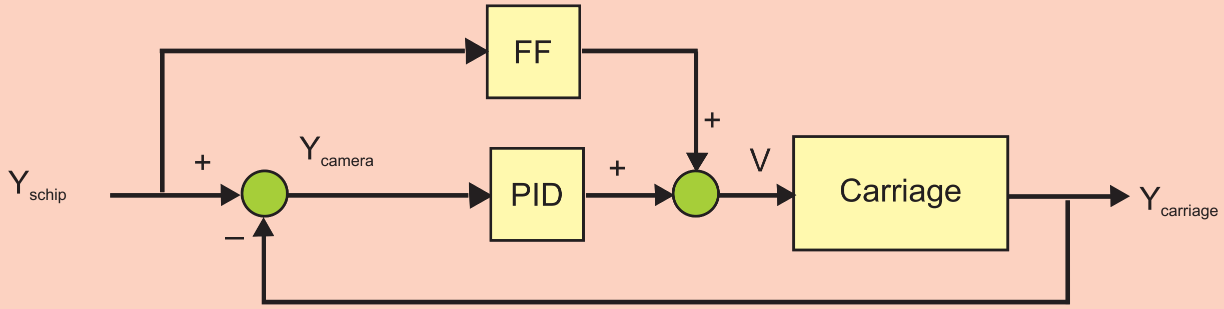

Figure 5: Extension with a feedforward controller that translates the measured ship position into a velocity signal for the motor controllers.

Design feedforward controller
To design a feedforward controller and testing its performance, a good model of the carriage is essential. Therefore all relevant parameters (i.e. dimensions, masses and stiffnesses) were extracted from the design drawings and documentation of the carriage. Next all carriage measurements were inspected. Using the parameters, partial models were created and verified with the relevant measurement data. An assembly of all partial models yielded the complete carriage model, which was again verified with the measurement data.

Carriage Subframe
The carriage model has been created in 20-sim. 20-sim is a software package for modeling and simulation which is suited very well for the modeling of computer controlled machines. The complete control loop of the carriage is implemented partially in a PLC, partially in an industrial PC and partially in the motor drives. All of the control loop parts run at different sample frequencies and are interconnected by analog electrical cables. This has all been carefully represented in the 20-sim carriage model. A part of the model, the carriage subframe, is shown in figure 6.

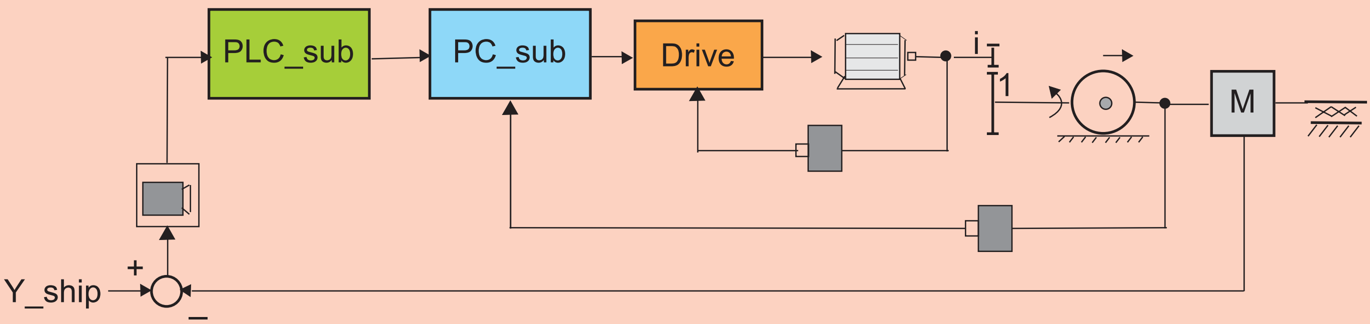

Figure 6: Model of the carriage subframe created in 20-sim.

Measurements
The model has been verified with measurement data. An example is shown in the plot of figure 7. This plot shows the position of the ship and carriage during a circle test in small waves.

During a circle test the ship is forced into a circle by giving the rudder a fixed angle. The measured ship is used in the model as an input variable. The simulated carriage response is compared with the real response.

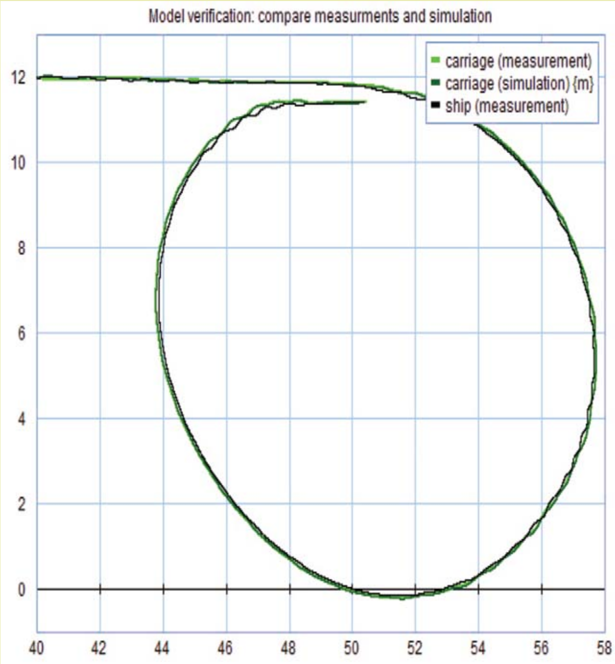

Figure 7: The simulation model shows very accurate predictions of the carriage behaviour.

The plot shows that the results of the simulation match the measurements very well (maximum error < 5%). The model predicts the carriage behaviour very accurately and can be used to design and test a feedforward controller.

State variable filter

Basically, the feedforward controller is a differentiation of the ship position to the ship speed. Because an exact differentiation is numerically impossible, a 'state variable filter' has been used. This filter is for low frequencies equivalent to a differentiation and suppresses disturbances for high frequencies. Because the filter has internal states, extra attention is given to the filter behaviour during state transitions and start-up. At these events, the filter must be given new starting values. A correct calculation of these starting values is very important.

Scenario's

The controller design was followed by a testing phase using the simulation model. First of all the feedforward controller was tested. Simulations showed a correct operation and a reduction of the tracking error of 70% ! Next robustness test were carried out during which the carriage behaviour under disturbances was tested. The simulations showed no deterioration of the robustness. Various scenarios were tested with the simulation model to inspect the correct operation of the safety layer and the correct handling of state transitions.

After the correct operation of the feedforward was determined, scenario's were ran for the implementation of the controller. The results of the simulations were documented in an implementation plan. This plan gave a step by step description of the tasks that have to be carried out to implement the feedforward controller and shows simulation plots with the expected results.

Results

An important demand of the Marin was that the implementation and testing of the adapted controller can only be performed during regular maintenance with a maximum time slot of 16 hours. After the implementation, the carriage should run flawlessly, because there is a very tight schedule of new ship model trials. Controllab Products was able to meet these demands. The controller was implemented successfully. The extensive implementation plan turned out to be very helpful. Especially the predicted carriage behaviour in the form of simulation plots was very useful, because it helped to quickly interpret the measurement results and track errors at the early stages of implementation. Moreover, the plots gave the commissioner great confidence in the correct implementation of the controller and resulted in a quick approval of the implementation.

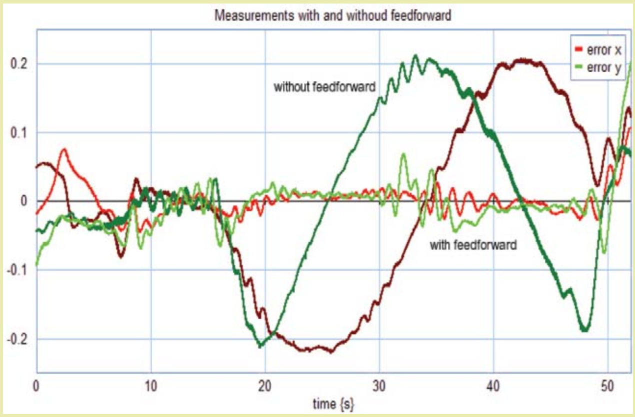

Figure 8: The carriage error during a circle test with and without feedforward control.

The measurements that were carried out during the implementation of the feedforward controller, confirmed the 20-sim simulation results. An example is shown in figure 8. This plot shows the carriage error (the distance of the carriage from the ship model) during a circle test. The circle test starts with the ship clamped to the carriage to bring it up to speed. At around 10 seconds the ship is released and the free running mode with feedforward controller is started. At around 15 seconds, the ships rudder angle is changed, forcing the ship to run in circles. The circle test was carried out in small waves. As the plot shows, the average error during the test is reduced by 70%. This creates a substantial margin for higher ship speeds. The Marin is confident that the carriage with the feedforward controller is able to track all modern high speed ship models.

More Information

Ir. C. Kleijn is the managing director of Controllab Products B.V. The company is a spin-off of the University of Twente in the Netherlands. Controllab Products was founded in 1995 and has specialized in the application of modeling and simulation. The company has gained a wide experience in improving machines and machine controllers. More information can be found on the website www.controllab.nl.