TUGNOLOGY '17
ROTTERDAM
Organised by The ABR Company Ltd

Increased Safety and Reduced Lifecycle Costs with Electronic Diesel Engine Management

Cyrill Halbauer (co-author/speaker), **Sebastian Schwarz** (co-author/speaker),
Timo Stache (co-author), **Thomas Schmauder** (co-author), MTU Friedrichshafen, Germany

SYNOPSIS
This paper demonstrates the potential for modern electronic control systems to enhance the operation of high speed marine diesel engines, thereby optimising their performance and the operational safety of the vessels in which they are used. We aim to demolish the myth that engine electronics unnecessarily add to the complexity of tug propulsion machinery. In addition, the paper should assist in understanding why electronic management systems are indispensable to meet current and future emissions legislation, reduce lifecycle costs and simplify both scheduled and unscheduled engine maintenance. Furthermore, we discuss the benefits of close interaction between the engine electronics and ship automation systems. Finally, the paper highlights progress in the field of electronic marine engine management on the basis of 20 years of MTU Series 4000 engine development.

INTRODUCTION
Today's marine diesel engine is a complex mechatronic system, having undergone a fascinating transformation from a pure mechanical device to a digitally controlled system. The first part of this paper outlines how and why diesel engines have metamorphosed so completely.

Ever since Rudolf Diesel filed his famous patent application in 1893, which forms the basis for the diesel engine, the main focus of improvement was optimisation of the fuel injection system. Subsequent major steps in the evolution of the diesel engine have always been largely dependent upon improvements in this area. This is also the reason why the electronic/ digital heart of today's engine is derived from a device invented to regulate the amount of fuel admitted to the combustion chamber – the engine governor. The evolution of the diesel engine management system can therefore be explained as the development of the fuel injection system and its governor.

DIESEL INJECTION SYSTEMS
Rudolf Diesel's original idea was to inject fuel directly into the cylinder, but since there were no suitable components available, such as pumps and valves, he needed to find a compromise. He used pressurised air to dose the liquid fuel and inject it vaporised into the combustion chamber. A major drawback of this setup was the necessity for powerful and heavy air compressors. Injection timing also depended heavily on the camshaft design.

In 1909 Prosper L'Orange eliminated this problem by inventing prechamber injection with a needle injection nozzle *(Figure 1)*. A controllable mechanically driven pump is used to inject the fuel into a small channel (prechamber) where it is vaporised by the combustion air which enters the prechamber from the cylinder. The fuel partly ignites, and the resulting expansion pushes the rest of the fuel into the cylinder where main combustion occurs.

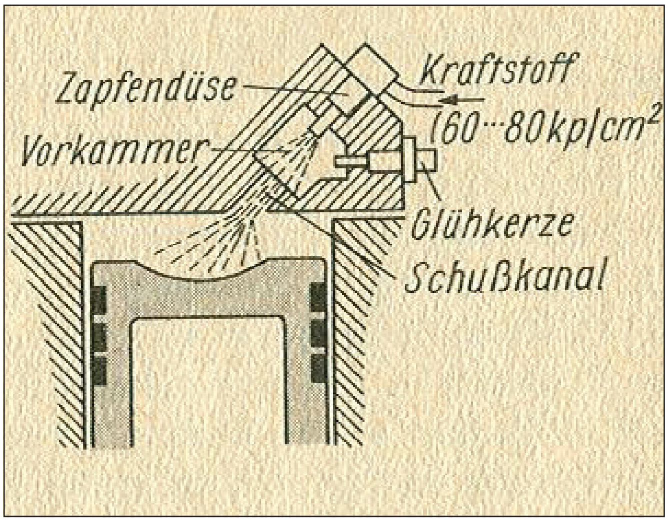


Figure 1: Prechamber injection[1]

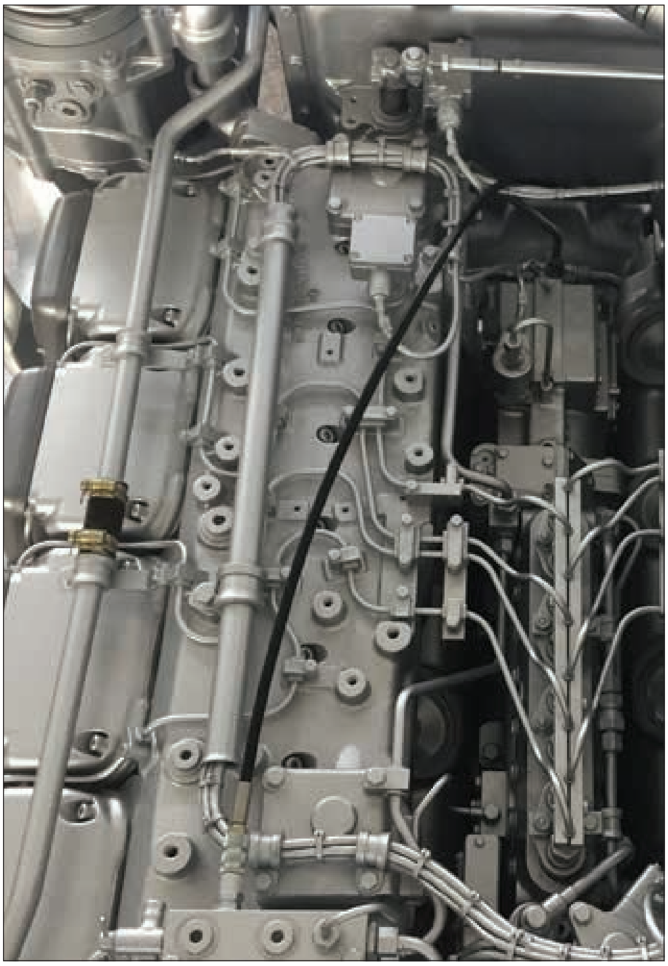


Figure 2: Fuel piping (central fuel pump to cylinders) on an MTU engine

By the start of the 20th century, all engines equipped with pressurised air injection had been replaced by engines featuring a prechamber injection system. This injection technology was used until the 1990s. For all injection systems using a main fuel pump, pressure build-up was performed using a single central pump. To make sure that the fuel was injected with the same pressure and at the same injection timing, the pipes connecting the pump to the nozzle had to be designed at an exact length for all cylinders, which caused a complicated piping layout *(see Figure 2)*.

At the end of the 1930s, the Detroit Diesel Company (DDC) in the US combined a camshaft-driven pump to each nozzle, forming an unit and thereby speeding the pressure build-up by eliminating the long pipes from the fuel pump to the cylinder. This system was the predecessor of the so-called unit injector system (UIS, or PDE). This system was further developed by controlling injection timing and duration using a solenoid valve. A derivative of this system is the unit pump system (UIP, or PLD), in which the pump is also driven by a camshaft but the nozzle is connected via a short pipe. This separation of pump and nozzle provides the engine designer with a larger degree of freedom in positioning the pump *(Figure 3)*.

The first US patent for the common rail injection system was issued in 1913. At the same time, UK firm Vickers also developed a system based on the principle of storing pressure in a vessel to use for fuel injection. It would take some time for this technology to prevail.

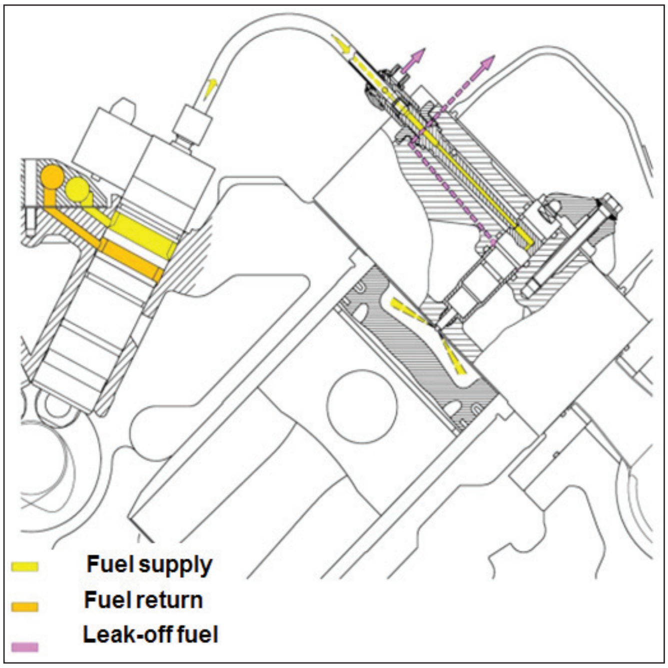


Figure 3: Unit pump system

Today the common rail injection system is most commonly used for high speed marine diesel engines. A common fuel pipeline, the so-called 'rail' that gives the system its name, supplies all the engine's fuel injectors with fuel. When fuel is to be injected into a cylinder, the system opens the nozzle of the relevant injector and the fuel flows from the rail into the combustion chamber, where it is atomised by the high pressure in the process and mixes with the air. Decoupling the pressure built up from the injection timing provides a large degree of freedom to optimise the injection process. This system was introduced with the MTU series 4000 in 1996 for the off-highway industry *(see Figure 4).*

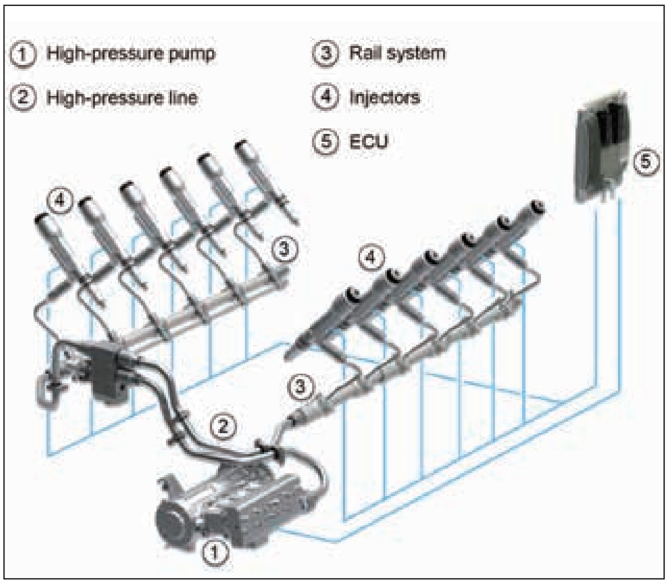


Figure 4: Common rail system

Each of the above fuel systems has its advantages and disadvantages, and have therefore remained in existence until today.

DIESEL ENGINE GOVERNORS

Directly related to, and associated with, the respective injection system is the device that controls the amount of fuel admitted to the cylinder, as well as the timing and duration of the injection: the engine governor. The history of governors may be divided into three generations: mechanical governors, electric (analogue) governors and digital governors.

Mechanical governor

Constant operating speed was a prerequisite for the use of mechanical devices during industrialisation. James Watt used a centrifugal governor to control the speed of his rotary steam engines. It was actually not the steam engine itself that was invented by Watt, but this optimised centrifugal speed governor, and the mix-up underlines how this device leveraged the steam engine development.

The design and layout of a centrifugal governor formed the origin of modern control and feedback control systems, as this device is an example of an early control loop with negative feedback *(Figure 5)*.

- The faster the engine is turning, the higher the centrifugal force acting on the counterweights on the levers;
- The counterweights are force-out and upwards-acting on a collar;
- The collar acts on a second lever which is used to control, eg, the amount of steam entering the cylinder of a steam engine.

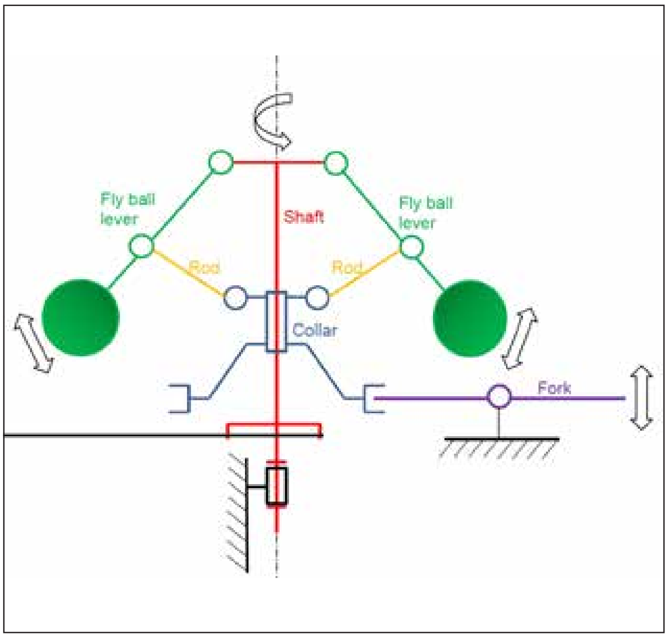


Figure 5: Centrifugal governor, working principle

The same principle was also used for a long period in diesel engines, although with a different design in more recent times. Centrifugal forces were used not only for controlling the amount of diesel entering the cylinder but also to govern the point of injection. With these devices it was (or is) quite easy to manually adjust the parameters within certain limits *(see also Figure 6)*.

The biggest drawbacks of this system from today's perspective are:

- The direct relation to engine speed;
- Mechanical vulnerability of the mechanical device, with possibly fatal consequences if engine over-speed occurs.

This governor laid the foundation for all future approaches. Already in these early days the engineers described the behaviour of this closed loop system mathematically and analysed the stability problem. Furthermore, they were able to articulate how the perfect governor should function:

"A perfect governor must not be called into action by a change in speed, but must feel the cause of such a change, and anticipate its effect, making the necessary adjustment before the threatened alteration in speed actually takes place." [2]

These early considerations led to the development of the PI and PID approach. Over the decades, the design was adapted and modernised. The purely mechanical linkage was replaced by oil-hydraulic systems or magnetic actuators, amplifying the power available to control valves (as is still done for the fuel injection systems of some marine diesel engines today).

At MTU the MTU 099 and 183 series were equipped with a purely mechanical governor, while the MTU 538, 956 and 1163 series used a mechanical hydraulic governor *(Figure 6)*.

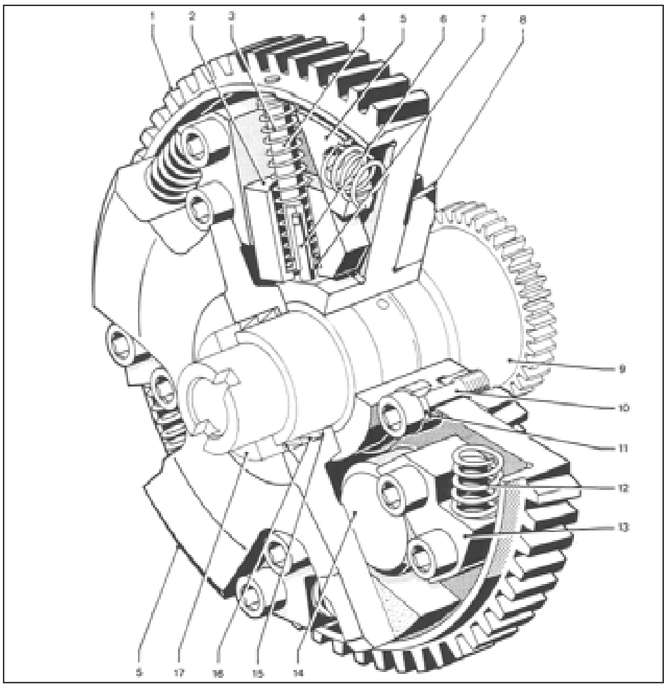


Figure 6: Mechanical (centrifugal) injection point adjuster (MTU 396)

Analogue electronic governor

Electronic governors emerged once engineers were able to use electricity as both an energy source and as an information carrier. Speed sensors deliver

information on the current operating condition as a constant information flow into an analogue circuit, which triggers a certain reaction to regulate the amount of fuel to be admitted for the combustion process.

The biggest advantage of the electronic governor is the accuracy and relative simplicity of (some) parameter adjustment. Furthermore, the system can be adapted for various operating conditions. The electronic governor opened up the possibility of governing multiple functions in one overall regulator. Now it was possible to not only govern fuel injection, but also to implement other functions, such as turbocharger switching or cylinder cut-off. Furthermore, all important state variables could be considered, and continuous engine monitoring by target/actual-value comparison became possible.

Regarding the automation industry, it may be underlined that mass production of governors has become possible only now, due to the fact that governors no longer need to be adapted manually for each machine, which increases the quality of the devices. Some of the disadvantages of mechanical governors, however, persisted:

- The structure of the PI/PID design is rigid. Changes require adaption of cabling and circuits;
- Sensitivity to ambient conditions;
- Ageing influence.

Electronic governors are still in use, but have a limited lifespan and have often been replaced by the next generation of governors. At MTU the electronic governor was already programmable to a certain extent by using a dedicated dialogue module, by which it was possible to determine maintenance intervals depending on the respective load and operation profile.

Digital electronic governors

Digital governors are implemented as PLCs (programmable logic controllers), and they provide the degree of freedom engineers were looking for from the beginning. Digital governors make it possible to process a vast amount of incoming information and derive the respective reactions from it, depending on software. All parameters may be varied and adapted by changing a few lines of code (or via a suitable user interface). All components of a digital governor can be enclosed in a protective casing, which makes the device resistant to external influences. Of course, one cannot visually inspect the unit (as with mechanical governors) or measure currents (as with electronic governors) to identify the causes of a malfunction, but in general the device is much more robust than its predecessors and all information can be accessed at any moment, including special error codes.

Today, then, it is possible to determine the beginning and end of the injection process, the numbers of injections per stroke, the fuel pressure and the amount of fuel, depending on various boundary conditions, and also to alter all these settings in case the engine requires it. All information on these processes can be viewed and delivered to the operator for information or stored for later analysis in case malfunction occurs.

MTU launched its first electronic engine controller module to reduce fuel consumption and increase performance back in 1982. The R082 and ECS UNI were fuel rack governors. In 1996 came the MDEC (MTU diesel engine controller), which was the first common rail governor worldwide and also the first electronic governor for unit pump injection systems. In 2004, the ECU 7 for the Series 2000 and 4000 engines followed, designated as an advanced diesel engine controller). The ECU 8, a special version, followed in 2008 for the Series 1600 engines. Three years later, MTU launched the ECU 9, also designated as an ADEC. All MTU marine engines available today are equipped with digital electronic governors *(Figure 7)*.

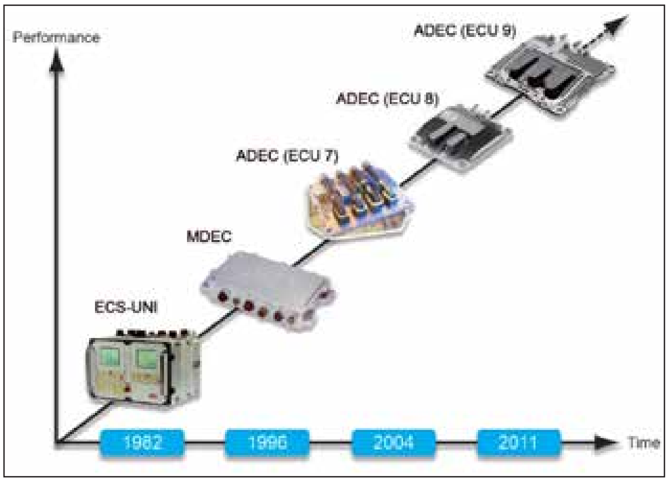


Figure 7: Development of MTU controller modules

MODERN MARINE DIESEL ENGINE GOVERNORS

A modern MTU S4000 tugboat engine features an electronic engine control unit (ECU), also called an ADEC (advanced diesel engine controller). The main functions of the ADEC are:

- Engine speed control;
- Injection control;
- Engine component actuation (eg, turbocharger switching);
- Engine monitoring and protection.

The ADEC contains functional software which is adjustable by parameters. By these it is possible to use the same functional software for different engine ratings, series and applications. Electronic governor adjustments are possible onboard with MTU's dialogue tool Diasys, which can be used to adjust, for example, the idle speed or engine speed ramps to meet ship-specific requirements.

Engine speed control

In marine applications, the ADEC is used as a variable speed controller. The ADEC receives the speed

demand from the control lever from an analogue current, or CAN signal. From this input, the ECU calculates the torque needed to reach the requested engine speed. The ECU then adjusts injection parameters as fuel pressure and injected fuel mass in order to stabilise engine speed within the power limits of the engine. This means that an ADEC engine cannot be overloaded. A higher load than the maximum continuous rating (MCR) curve will only lead to a drop in engine speed. A marine engine controlled by a speed governor enables smoother operation compared to a load controlled engine, which reacts with varying propeller speeds in, for example, rough sea conditions.

Injection control

Modern MTU series 4000 engines are equipped with a common-rail fuel injection system which consists of the following components *(see also Figure 4)*:

- Low pressure fuel pump – supplies the high pressure pumps with filtered fuel;
- High pressure pump – supplies high pressure fuel to the rails. A pulse width modulated signal from the ECU keeps the pressure level of the fuel at the optimum level as a function of engine speed and load;
- High pressure sensor – measures fuel pressure in the rails. The ECU uses this signal to control the high pressure pump;
- Injectors – injection of fuel into the combustion chamber. Injection timing, including pre- and post-injection, is ECU-controlled.

Figure 8 illustrates the fuel system with pumps, filters as well as monitoring devices.

The high pressure fuel pump continuously supplies pressurised fuel via the rails to the injectors. The fuel mass injected into the combustion chamber depends on fuel pressure and the duration of injection. The injection duration is controlled by the timing of the electric current supplied to the injectors by the ECU.

The common rail fuel pressure is controlled by the variation of the fuel flow entering the high pressure pump. This is done by a pulse width modulated (PWM) solenoid valve which is governed by the ECU.

Based on these parameters, fuel consumption in ltrs/hr is calculated and transmitted via the CAN to the automation system display. Based on the injected fuel and an engine-specific efficiency table, the engine load is also calculated. Engine load is an important value, used to determine in which area of the performance diagram the engine is operating *(see Figure 9)*.

The ECU parameters, engine load and load reserve all provide valuable information in combination with the vessel propulsion system, enabling (for example) pitch control of CP propellers or combinator curve (speed-pitch) based control strategies.

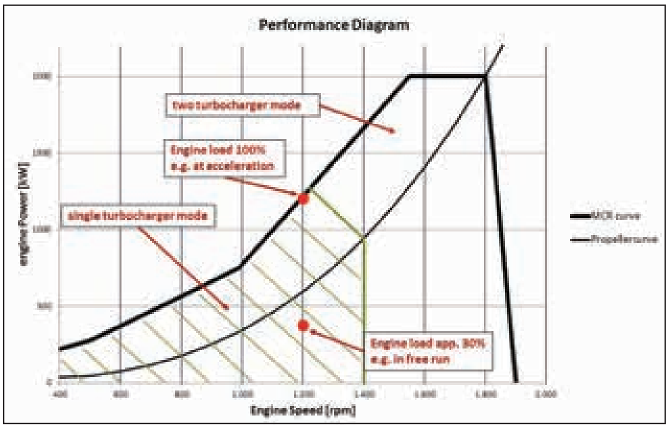


Figure 9: Performance diagram (schematic)

Multiple injection

A great benefit of electronic engine governors is the possibility of pre- and post-injection. Whereas pre-injection helps to reduce engine noise, post injection can be applied to reduce emissions of particulate matter. Soot formation during combustion in a direct injection diesel engine is unavoidable. It occurs in zones with high temperatures and high fuel/air ratios. Usually most of the soot generated during the first phases of combustion is converted to carbon dioxide during the beginning of expansion at the top dead-centre of the piston, because the mixing energy and

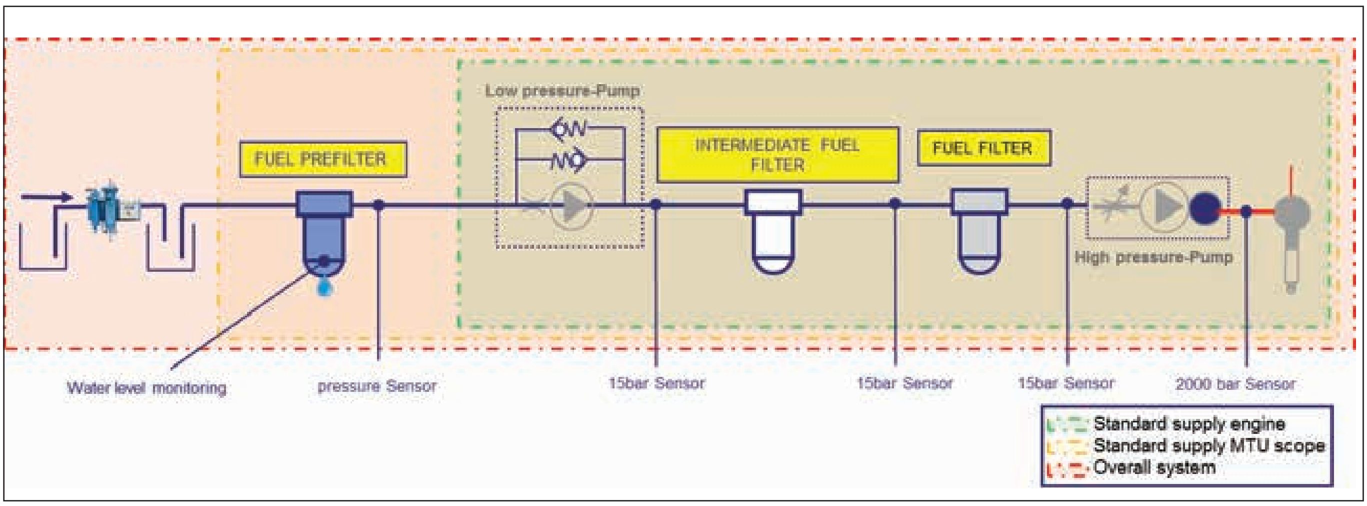


Figure 8: MTU fuel system sensors and monitoring

temperature are still very high. With increasing volume, the temperature and turbulence level of the cylinder charge decreases and soot oxidation slows down until it freezes completely. The remaining amount of soot can be found in the exhaust gas and represents the main element of particulate emissions.

Post injection is the additional injection sequence of a small amount of fuel after the main injection is already completed. The ignition and burning of the second fuel amount increases the temperature of the cylinder charge, and the impulse of the second fuel jet increases turbulence and mixing within the cylinder charge. This leads to an extension of the soot oxidation period during expansion, and therewith to a reduction of particulate emissions.

Calibration drift compensation (CDC)

Over the lifetime of the engine, wear, ageing and the drifting phenomena of components have an influence on both emissions and performance. When these changes are understood and their characteristics over the lifetime of the engine can be described, it is possible to counteract them with compensating measures designed to minimise changes in harmful emissions over the engine's lifetime.

The calibration drift compensation (CDC) functions are active throughout the life of the engine and during all operating conditions. To compensate for injector wear, for instance, the ADEC calculates a virtual injector age for every injector, based on engine speed and injections. When an injector must be replaced, the counter for that individual component is set to zero. The CDC adjusts the engagement time of the injectors, the beginning of injection (BOI) and rail pressure to optimise emissions and engine performance over the engine's lifetime, and helps to avoid excessive engine wear due to abnormal vibration caused by cylinder misfiring.

Engine protection at hot ambient conditions

In hot ambient conditions (>45 degrees C intake air temperature) the thermal load for an internal combustion engine is very high. To avoid engine damage, a so-called hot ambient condition control system within the ECU is used to prevent the engine, particularly the exhaust system and turbochargers, from thermal overload. The hot ambient control system limits torque, depending on the ambient temperature, and adjusts the BOI to reduce the thermal load, and any exhaust opacity/smoke due to lack of oxygen.

Black smoke control

During transient operation with fast acceleration, a lack of air mass caused by natural turbocharger lag (the delayed response of the turbocharger) may occur. The amount of fuel injection in such situations is temporarily adjusted by the ADEC, because insufficient air for an ideal combustion would only cause excessive black smoke, and not additional torque. This strategy is called 'dynamic injection timing', or black smoke control.

It helps to prevent black smoke during acceleration manoeuvres, combined with ensuring maximum fuel efficiency and maximum engine power at steady state operation.

Figure 10 shows the 3D map of the black smoke control, which defines the maximum injected fuel mass (Z-axis) depending on engine speed (X-axis) and charge air mass (Y-axis).

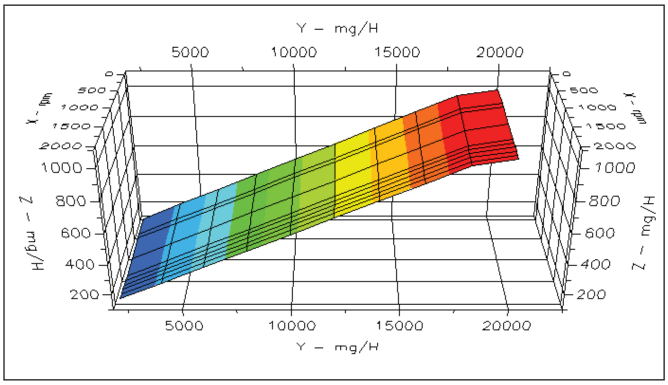


Figure 10: 3D map of the black smoke control

Turbocharger control

To produce engine performance which delivers enough torque at low engine speed for safe manoeuvring or crash stop manoeuvres, and which delivers maximum power at full engine speed for maximum bollard pull or vessel speed, modern diesel engines are equipped with variable turbocharger geometry, two-stage turbocharging or sequentially shifted turbochargers. The primary turbocharger is always active. The second turbocharger is switched in at a defined turbocharger speed or engine speed, depending on which limit is reached first. Turbocharger shifting ensures sufficient boost pressure for low load operation, just as for high load operation, where a much higher air mass is requested by the engine *(Figure 11)*.

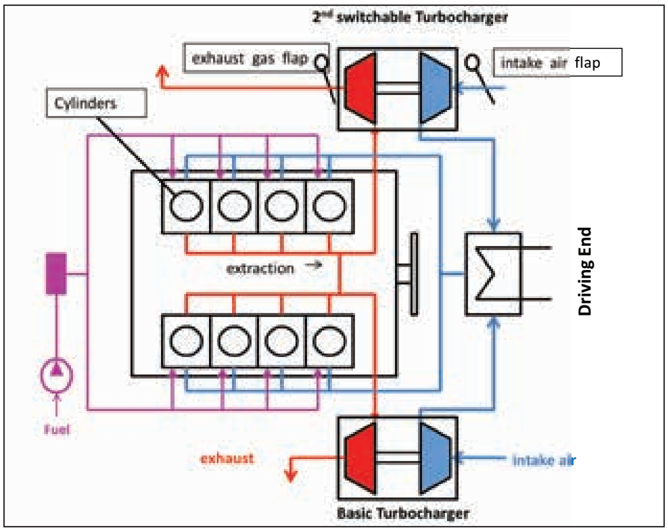


Figure 11: MTU engine combustion/exhaust schematic

Turbocharger shifting is completely controlled by the ADEC, which actuates electromagnetic valves to move the exhaust and intake air flap at the switchable turbocharger.

Engine monitoring and protection

Modern marine diesel engines are equipped with a comprehensive set of sensors for engine monitoring and protection. Usually an engine protection module consists of two limit values, or engine speed dependent limit curves (2D curves). The first limit is in most cases a visual warning (yellow alarm) to the crew, displayed as a clear text message. The second limit triggers an automatic engine protection function (red alarm) such as power or speed reduction, or an engine shutdown. As the captain must retain overall control, he can use an override function in an emergency situation to overrule most engine self-protection mechanisms.

Certain failure modes that cause immediate engine total damage, such as low lube oil pressure, engine overspeed and high crankcase pressure, are not allowed to be overwridden. This is because override would lengthen the operation of the vessel only for split seconds, and the consequence of an engine failure resulting from above incidents poses a very high risk for the crew.

The benefits of these monitoring and protection functions can be split into two categories: monitoring of maintenance related parameters, and monitoring and (self-)protection of function-critical parameters.

Maintenance-related monitoring functions cover, for example, differential pressure monitoring over engine oil and fuel filters as an indication of clogged filters. If a differential pressure reaches the predefined limit value, a yellow alarm will be displayed. This allows maintenance on demand, rather than time-triggered only, and consequently reduces maintenance time and spare parts costs. In addition, automatic alarm notifications free the crew from secondary jobs like checking gauges for the correct values. On-demand maintenance can help to avoid major follow up costs, such as those caused by particles dispensed from clogged filters which head downstream to damage high pressure fuel components *(see also Figure 8)*.

For functional-critical parameters, an automatic engine reaction is triggered by the respective protection module, and occurs after the pre-warning. In the cases of high temperatures for coolant water, lube oil, fuel, charge air and exhaust gases, an engine speed- or power reduction will typically trigger in order to cool the medium down to an acceptable value. The degree of engine speed reduction depends on the limit deviation – the more the limit is exceeded by, the greater the engine speed reduction.

Example: Speed reduction at high lube oil temperature

Figure 12 shows an engine reaction simulation involving exceeding Limit 2 for high oil temperature (red alarm at 101 degrees C). The Limit 1 alarm (yellow at 95 degrees C) is not visualised here, as it triggers no automatic engine reaction. In Area 1, the oil temperature is below its second limit and the engine is at a constant speed of 1,800 rev/min. In Area 2, the oil temperature exceeds the Limit 2 value of 101 degrees C, and after a time delay, a smooth automatic engine speed reduction begins. As the limit deviation rises in this simulation case (Area 3), engine speed reduction becomes stronger, until the oil temperature falls below its limit (Area 4) and the engine speed ramps up to 1,800 rev/min again.

Example: Engine shutdown due to high crankcase pressure

This is a good example of how powerful crankcase pressure monitoring is. *Figure 13, overleaf* shows damage suffered by an R&D test engine during an endurance run. The root cause was a broken piston pin ring snap, which damaged one piston and cylinder liner. As a consequence, the crankcase pressure increased

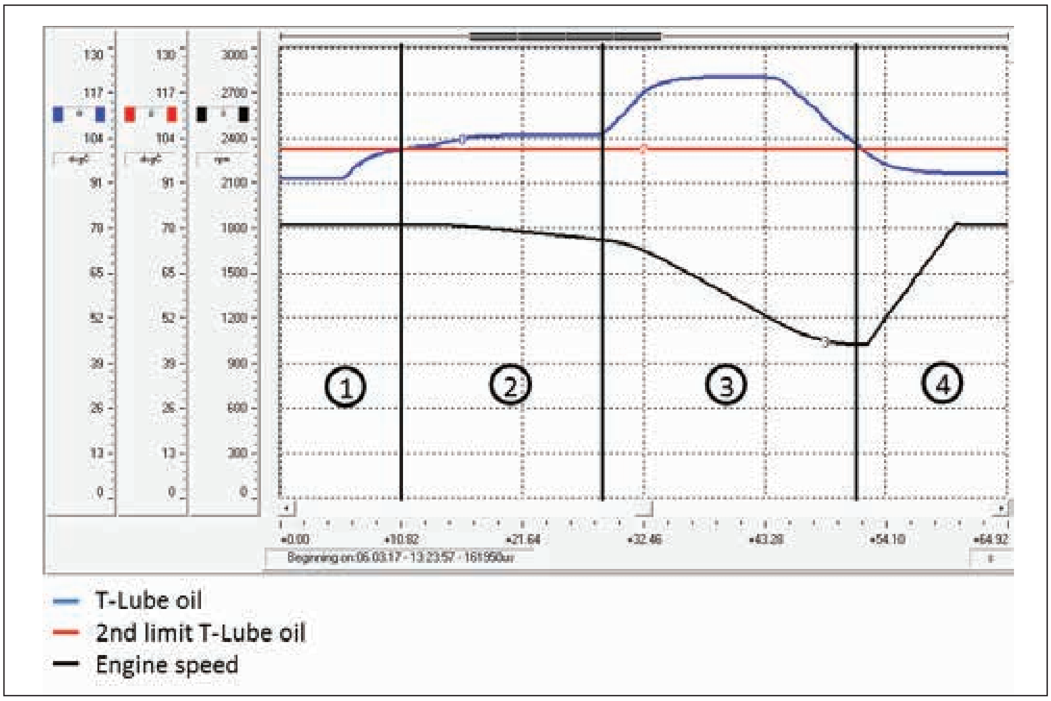


Figure 12: Graph engine reaction simulation

due to 'blow by' gas. *Figure 14* shows the trend of the crankcase pressure recorded during the test run. The time between the two measurement points is one hour. The trend shows a clear indication a few hours before the engine was automatically stopped by the protection system at the limit value of 40mbar.

Figure 13: Damage on piston and cylinder liner

In addition, the exhaust gas temperature monitoring shows a clear indication of which cylinder was damaged *(see Figure 15)*. Without the crankcase monitoring function, follow up failures would have most likely led to total engine damage. Due to the design of the single cylinder heads, pistons and cylinder liners can be changed quite simply.

Load profile recorder

The engine-integrated load profile recorder is the pre-condition for a flexible maintenance concept matching a real operating profile and the wear and tear of the engine. The fundamental concept, and positive effects on maintenance costs, are described in the reference paper *Optimising the Total Cost of Ownership by Customised Maintenance Concepts*.[3]

Crash recorder

The ADEC also includes a data logging function called a crash recorder. The crash recorder is triggered by severe alarms, or in the case of the engines stalling. The ECU continuously stores the most important engine data, such as engine speed, engine load, pressures and temperatures, in a ring buffer.

If the trigger activates, data from the ring buffer gets stored. In this way, historical engine data can be read after a fatal engine failure for root-cause analysis. This data is also helpful for root-cause analysis of ship collision accidents, due to the trigger at the point the engines stalled.

Interfaces

The ADEC sends all alarms, sensor values, engine load and actual fuel consumption, via CAN, to the monitoring and control system displays. Required input values such as start and stop signals, speed demand and override requests are received via CAN or analogue inputs depending on the remote control system used. For maximum safety, the emergency stop function uses a discrete route to stop the engine under all circumstances, even if the redundant CAN bus is defective.

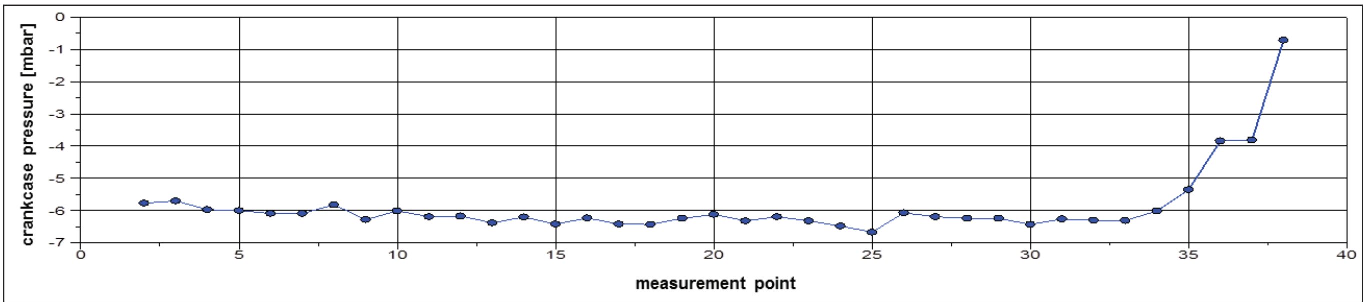


Figure 14: Crankcase pressure monitoring

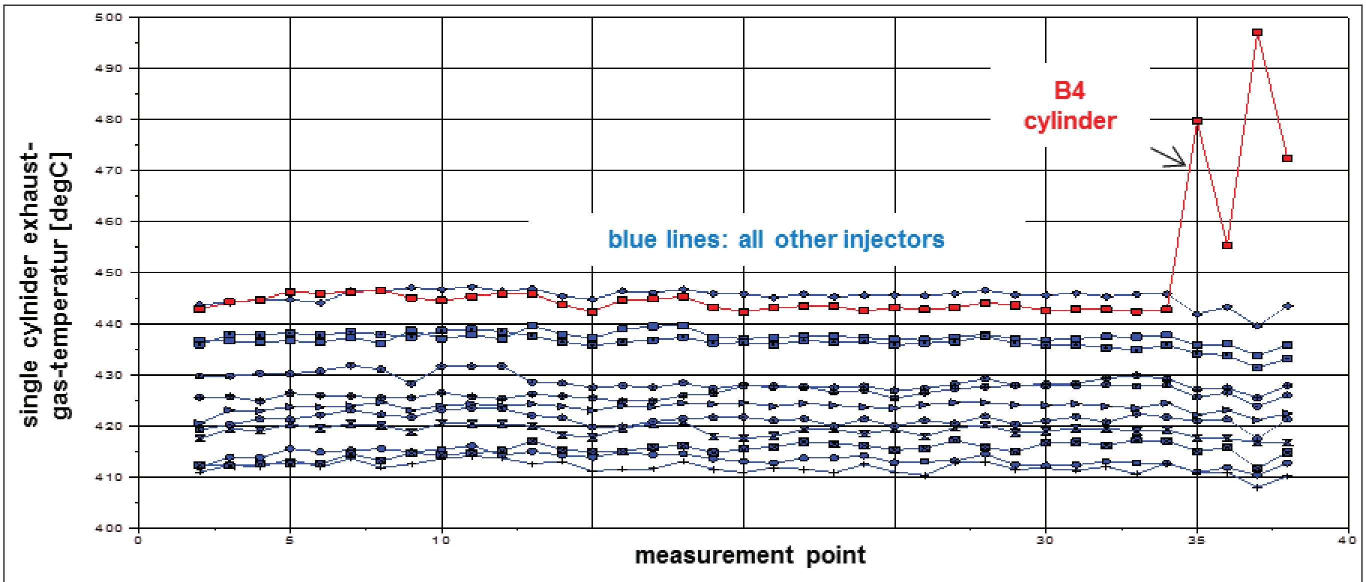


Figure 15: Single exhaust gas temperature monitoring

Remote services

In this digital age, data from the engines is not limited to the vessel, and there are benefits to sending it onshore. Through remote troubleshooting, downtimes can be reduced as alarms and sensor data are transmitted and stored onshore. The service engineer can prepare his trip with the correct spare parts, or a service trip can be saved as the crew can be advised on how to fix a problem by themselves. Fuel consumption can also be optimised by analysing the data, for example, to monitor the idle times of the engines or to determine the most economic ship speed. The MTU Remote Services system incorporates a telemetric device which reads selected data and sends it to a server via cellular network or by using the shipside communication system. The data can be visualised and exported to third-party systems via web-based access.

HISTORY OF SHIP AUTOMATION

Ship automation can be defined as the application of a superordinate technical authority that can monitor, control, alarm and record various ship systems. Technological progress, especially in the marine environment, is not always enthusiastically welcomed. Even if technical innovations have been extensively used in other fields, the shipbuilding industry has often adopted ideas slowly. Regarding automation systems on ships, this reticence may be justified by the very high requirements of any equipment used in such a harsh environment.

It was only in 1961 when the first automated vessel (according to the modern understanding of automation), the Japanese seagoing ship ***Kinkasan Maru***, started its maiden voyage. The vessel featured bridge control for its main propulsion plant and a centralised control system for all engine room machinery. In subsequent years the development of automation systems for ships was mainly driven by developments in Japan and Scandinavia (Norway in particular), in both cases due to a lack of qualified seamen and because they understood very early the impact that automation would have on the entire marine industry. They assumed that even if the investment cost was very high, the benefits would still give a greater return by:

- improving operating efficiency;
- increasing safety;
- reducing maintenance costs;
- avoiding unscheduled repairs and downtime.

From the technical point of view, the history of ship automation systems can be looked at as a history of separation. It is a history illustrating how the controlling and intervening entity has untied itself further and further from the machine or system it is controlling.

This development can be observed in the development of the marine diesel engine. In the early days, all monitoring and controlling had to be performed on the machines directly. Human sensory reception was as important as any rudimentary indicators mounted on the components. A good engineer had to be able to judge by the sound emitted from the engine's cylinders whether they were in a healthy condition. In case something was wrong, there was no alarm system beyond the deduction of the engineer.

In addition, control of the vessel's speed had to be done on the engine directly through the use of a dedicated control lever mounted to the engine that regulated the amount of fuel entering the combustion chambers. From the 19th century up until the 1950s, the engine order telegraph (also called the chadburn) was the only available network transmitting orders from the bridge to speed up or slow down the engine. Humans were the interfaces, and manipulating the engine had to be done on-site.

The first step towards separation was to fit manometers and thermometers directly on to engine components. The engineer still had to walk around the engine inspecting all relevant components. The next phase was to combine all manometers and thermometers into one box, which could only be mounted directly on to the engine due to the restricted reach of the capillary thermometers used. There was no alarm in case limits were violated. Alarms and subsequent engine reaction were executed by the responsible engineer.

Technical progress made it possible to move the displays further away from the information source and create a box combining all displays in a remote location, albeit one that still had to be mounted in the engine room. During the 1970s it was common to transfer data directly measured in the engine via analogue interfaces to the bridge. Such a system was in use at MTU until the end of the 1980s. All components for MTU engine monitoring were originally developed for the use on the MTU test benches where the engines had been calibrated and tested before their delivery to customer. A clever engineering team at MTU optimised and adapted the devices to use them for engines operating in the field *(see Figures 16 and 17).*

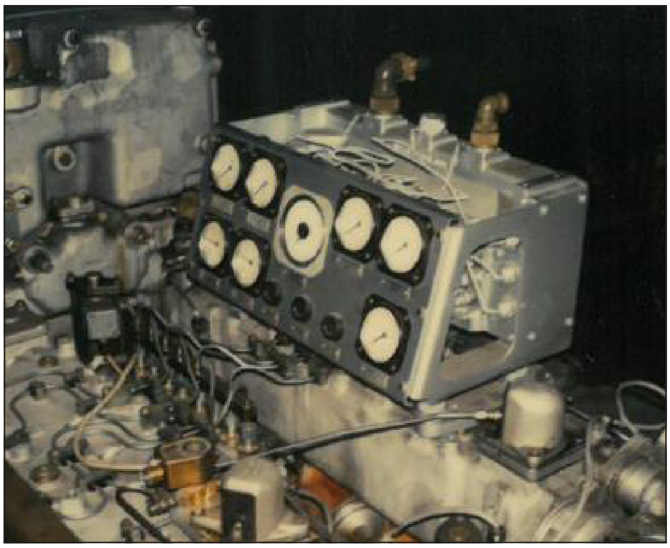


Figure 16: MTU 'Zeidler' box collecting information via capillary thermometers and manometers

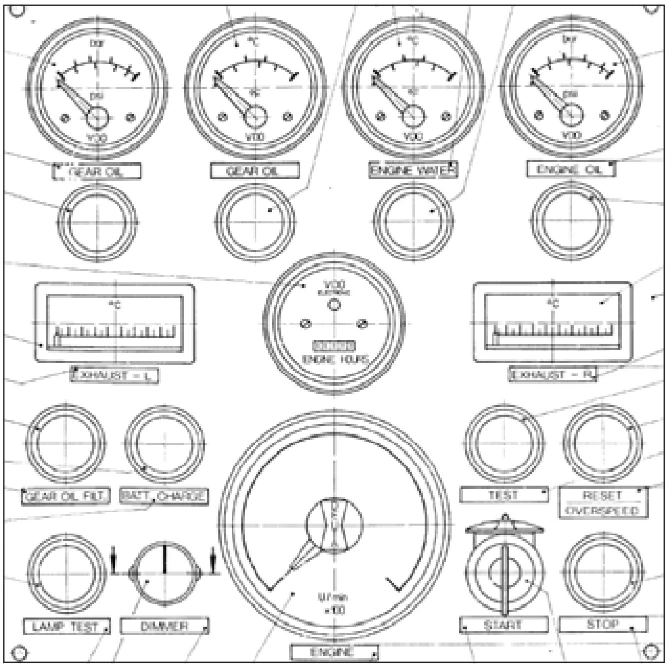


Figure 17: A bridge display from 1976. Each display was customised for each project

Even once the use of advanced sensors became commonplace, only one display could directly present the measurement of one sensor, due to the restrictions of analogue systems. It was still only possible to create one main control stand, which was normally still positioned in the engine room and under the responsibility of the engineer.

When digital monitoring and control systems were introduced, it was a quantum leap. From that point on there were no longer restrictions regarding the distance and number of displays. Furthermore, limit violations could now directly trigger not only an alarm, but also an engine reaction. The separation between the engine and its controller was extended to the bridge. The possibility of classing a vessel for 24 hours of unattended machinery space reflects the confidence we have in the capabilities of modern automation systems.

And this is not the end of the story. The engine, propellers and other machinery, as well as all other ship's systems, may be monitored, or theoretically even controlled, from the shore – even a head office on another continent, by means of available remote service solutions. Such solutions have actually been in existence since the 1970s using satellite information exchange between a vessel and a land-based station to monitor engine condition. The ultimate separation step discussed at the moment is to detach humans from the control of all kinds of vessels by designing fully unmanned systems. The technology is already there, and it will be only a matter of time until we see the first ships sailing the oceans without any crew. Whether this is a desirable objective is a different matter.

MODERN PROPULSION AUTOMATION SYSTEMS

Modern vessels require modern engine technology, which in turn requires at least an electronic engine system. The electronic control and monitoring of engines, propulsion and general ship operation has become more and more important. In order to meet the increasing complexity of today's marine propulsion systems, modern monitoring and control systems are essential.

The MTU Blue Vision | NewGeneration[4] system, based on new MCS-6 technology, has its focus on the automation of ships' propulsion plants. The automation system consists of a monitoring control system (MCS) and a remote control system (RCS). It is connected to the engine control system (ECS), the gearbox, the propulsion and the auxiliary systems via interfaces *(see Figure 19, next page)*. The application engineering includes the adaption of the system to specific application requirements, and also includes the diagnostics during commissioning and service.

The local operating panel (LOP) is the central component in the Blue Vision | New Generation automation system *(Figure 18)*. It is always allocated individually to one shaft. The LOP has its functions as a local control stand in the engine room, and comprises the systembus processing unit (SPU) in combination with an operating unit and the local operating station (LOS).

The SPU contains two independent modules for MCS and RCS. The MCS module monitors the engine and gearbox as well as additional drive related signals. The RCS module is the central unit for remote control of the propulsion system. In addition, it monitors the extended range of signals for classified installations. As an alternative to an MTU RCS, it is also possible to connect a remote control system from a third-party supplier to the non-MTU RCS interface on the SPU, transferring the signals directly to the ECS and the gearbox. The LOS is in turn connected via the MCS module in order to be independent of the RCS module.

Figure 18: Local operating panel

Monitoring control system (MCS)

The task of the MCS is to monitor the entire propulsion plant. For this purpose, sensor signals are recorded, evaluated and represented on instruments and displays. The MCS of today's propulsion plants are linked to the ECS via a data bus, such as a CAN-Bus or Ethernet. It receives the sensor signals, status information and alarms which have been generated

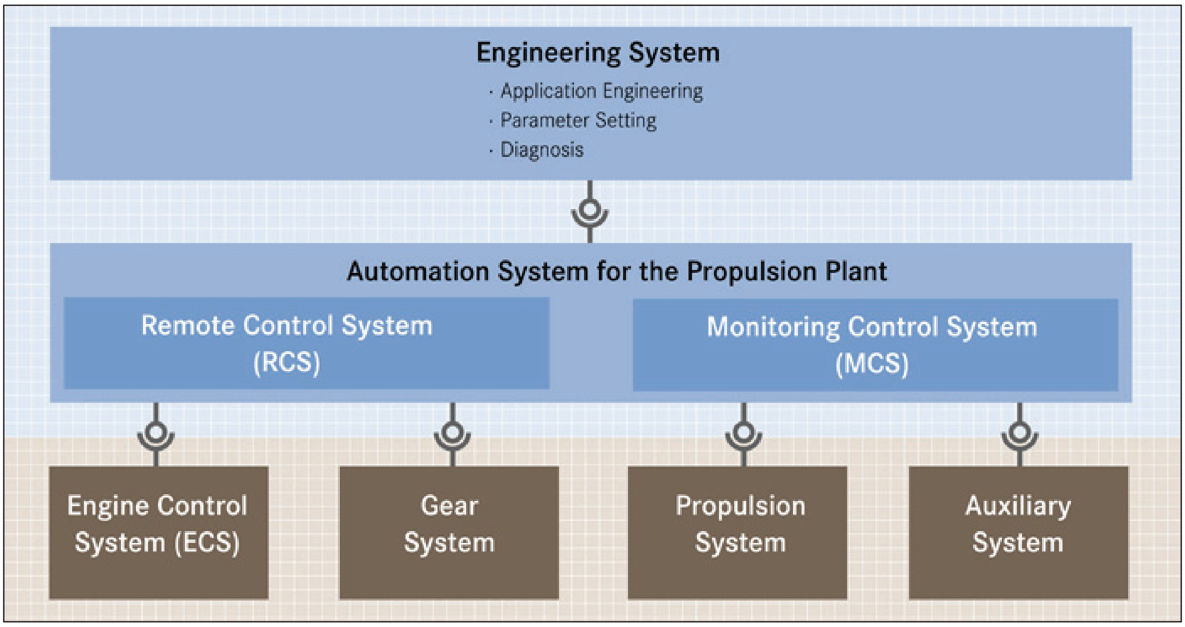


Figure 19: Automation system for the propulsion plant

from the various information held within the engine control unit (ECU). All the propulsion drive components (gearboxes, propellers, shaftbreaks, etc) can be directly connected to the automation system and evaluated by the monitoring control system.

By gathering all relevant information in a central monitoring system, data can be presented to the operator in a user-optimised layout. If required, the operator can also check every individual sensor monitored by the ECS system or the higher level automation system. The Blue Vision | NewGeneration system offers various display pages, such as the engine overview page *(Figure 20)* or the measuring point list *(Figure 21)*.

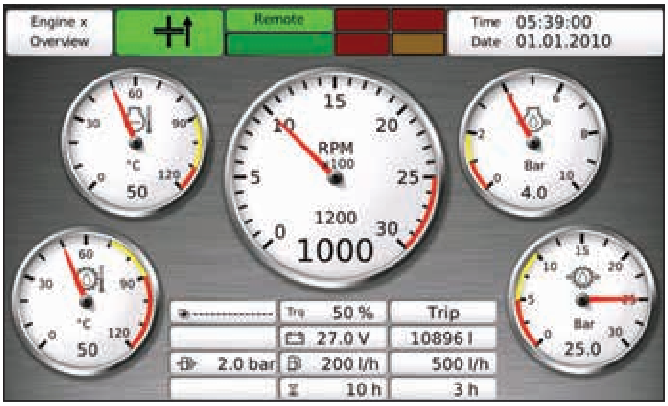
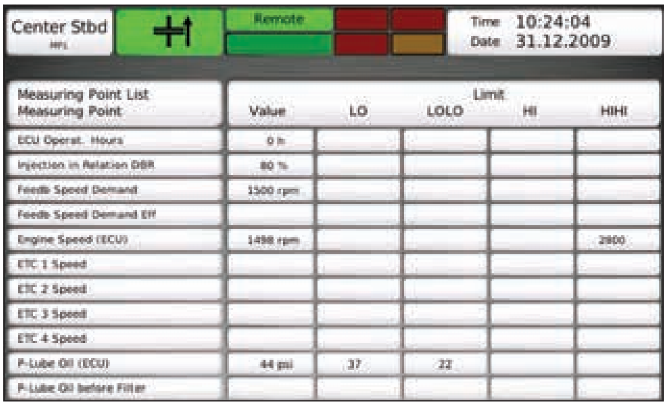


Figure 20: BasicDIS – Engine overview



Measuring Point List / Measuring Point	Value	Limit LO	LOLO	HI	HIHI
ECU Operat. Hours	0 h				
Injection in Relation DBR	80 %				
Feedb Speed Demand	1500 rpm				
Feedb Speed Demand Eff					
Engine Speed (ECU)	1498 rpm				2800
ETC 1 Speed					
ETC 2 Speed					
ETC 3 Speed					
ETC 4 Speed					
P-Lube Oil (ECU)	44 psi	37	22		
P-Lube Oil before Filter					

Figure 21: BasicDIS – Measuring point list

The alarm generation, signalling and acknowledgment system represents a fundamental component of the MCS. While the operator concentrates on manoeuvres and the vessel's movement, the automation system autonomously monitors the complete propulsion system. If the monitoring system detects the violation of a limit value (such as high coolant temperature) or any other alarming event, a dedicated alarm will be created. The alarm notification will be shown in the control stand display using a distinct alarm code, but also by an easy to understand alarm text.

In addition to the short alarm text, an additional alarm description can be shown in the display to support the operator in an optimised manner. The alarm description clearly explains the meaning of the alarm, the impact and corrective actions *(Figure 22)*.

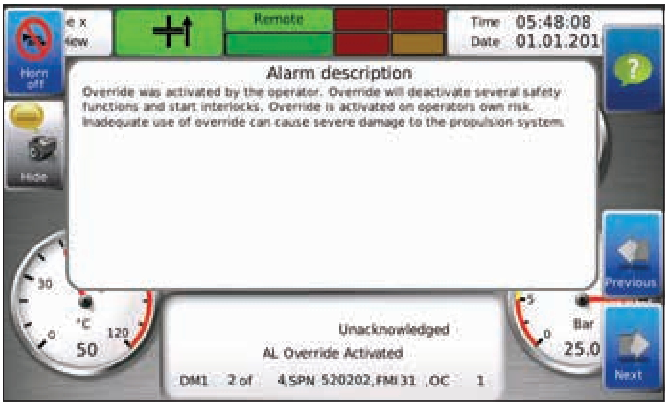


Figure 22: Basics – Alarm message and description

After returning to the harbour, or in the case of service activities, all alarm history can be recalled directly. The alarm history allows the reconstruction of the alarm situation, enabling an advanced failure diagnosis to support specific measures and to avoid future issues resulting from the same source.

Remote control system (RCS)

The RCS is a remote control system for the propulsion plant. The RCS is subdivided into the local control stand

in the engine room and the control units on the control stands. The RCS has the task of controlling engine speed and gearbox state input signals. The input signals from the control unit of the active control stand are transmitted to the engine control system and the clutch valves on the gearbox. For propulsion systems with CP propellers, the control of the pitch position is also one of the important functions of the RCS.

The advantages of an electronic remote control system are the increased flexibility, together with increased safety, of the operation of the vessel's propulsion system. The operator can be assisted by automatic control sequences such as:

- automatic engine start sequence with pre-lubrication;
- profile-dependent drive modes for reduction of fuel consumption and comfortable manoeuvring;
- crash stop manoeuvre.

In addition, the system can act with 'intelligence'. It can verify and control inputs from the operator by use of status information in order to prevent avoidable damage.

Development according to the specifications of the class societies

To register a ship with a classification society, the shipyard must present extensive verification records, including verification of the automation system for the propulsion plant. If these verification documents are already available, this simplifies the classification process significantly.

At MTU Friedrichshafen, all components for use in classified systems are provided with a Type Approval for the major classification societies. MTU develops all hardware and software components according to the familiar V-model. This procedure contributes to avoiding systematic faults during product development.

The development process for Blue Vision | New Generation was specially tailored to the specifications of the leading classification societies, and was presented to them at an early stage of development.

COMBINING ELECTRONIC ENGINE AND VESSEL MANAGEMENT, CONTROL AND MONITORING SYSTEMS TO ENHANCE SAFETY AND OPERATING COSTS

In the past, with mechanical propulsion control systems, the captain was responsible for the precise control of all equipment – in particular, steering, propeller speed and pitch (in the case of controllable pitch propulsors). Consequently, safe operation in extreme environmental conditions challenged the captain and crew to their limits, particularly when signs of equipment malfunction occurred in parallel. Here we describe the benefits of modern electronics systems based on the examples of a crash stop manoeuvre, advanced CPP control and fi-fi operating modes.

Crash stop for conventional FPP propulsion system

Crash stop means bringing the vessel to a standstill as quickly as possible in an emergency situation while simultaneously maintaining manoeuvrability. Focusing on the propulsion control system, the typical sequence of a crash stop can be summarised as:

- detecting the need for a crash stop;
- reducing engine and propeller speed;
- disengaging gear-clutch ahead;
- vessel speed reduction in neutral;
- engaging gear-clutch reverse;
- increasing engine and propeller speed reverse;
- disengage gear when vessel stopped.

In the past, engine speed was very often the only criterion used to initiate the crash stop clutch control for most systems. In the worst case, some RCS systems did not even have differentiation criteria, and it was the responsibility of the operator to follow the sequence without stalling the engine.

In modern RCS systems, vessel speed has now been included as an additional criterion. This ensures that clutching is always possible at a certain speed regardless of any external influences (wind, current, loading, etc). The system calculates speed on the basis of a theoretical model comprising engine speed and shaft speed. Disengaging and engaging the gear clutch can be optimised by calculating vessel speed in this way. This calculated ship model is robust and reliable even without relying on external information. However, external ship speed signals could also be considered. The clutch sequence of the BlueVision | NewGeneration system can be divided into three ship operating windows *(Figure 23)*, which are calculated based on the integrated ship speed model.

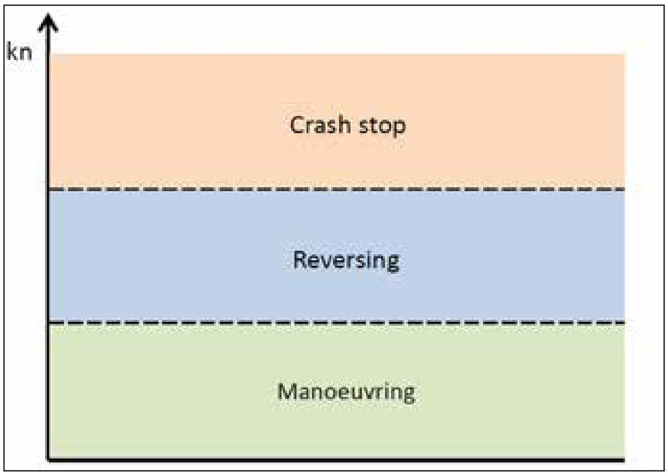


Figure 23: Clutch sequence ranges

In the first manoeuvring range, with low ship and engine speed, it is possible to engage and disengage the clutch without significant delays (apart from those usually associated with this technology) and without any additional measures (such as an engine speed increase).

The second reversing range begins at the defined ship speed at which reverse clutch engagement is possible without additional measures or excessive engine speed dip. A clutch sequence initiated at a ship speed in this range is called 'reversing'. Within this range, the clutch and speed control is directly connected to the lever movement and the clutch engagement is only controlled as a function of the clutch speed window.

The third crash stop range is determined by a high ship speed limit, above which reverse clutch engagement is no longer possible without stalling the engine unless additional measures are taken. The crash stop manoeuvre is detected by a rapid lever movement from ahead to astern. Depending on the vessel speed, the optimal timing for the disengagement of the clutch and the earliest possible timing for the reverse engagement in combination with temporary engine speed increase can be calculated in the RCS. This speed-dependent sequence allows an optimal braking distance without the risk of stalling the engine.

The automation functions of special relevance for the crash stop optimisation can be summarised as:

- ship speed model;
- engine acceleration ramps up and down;
- gear clutch control logic and speed window;
- temporary engine speed increase before reverse clutch engagement.

Additional features, such as shaft brakes, can also be used to support an optimisation of the vessel's braking distance. However, such equipment increases vessel cost, which could be avoided by smart interaction of remote controls and diesel engine.

Advanced CPP control

Advanced electronic remote controls enable efficient, comfortable and safe operation of CP propelled vessels. According to the various operating profiles of a vessel, multiple combinator curves for engine speed and pitch demand can be handled by the RCS.

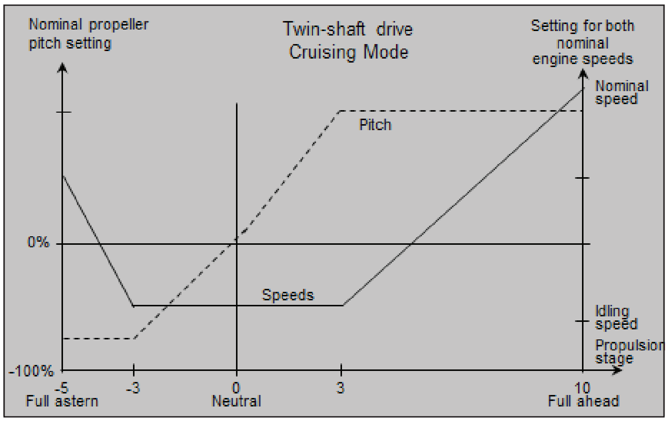


Figure 24: Combinator curve cruising mode (example)

For example, for a typical tug application, different curves for transit (fuel economy) and for the job (bollard pull) can be integrated into the drive curve settings. *Figure 24* shows a combinator curve example for a conventional twin screw CP propeller installation, where engine speed and propeller pitch angle are simultaneously changed as a function of the lever position. With the automatic load control of the RCS it is possible to prevent an engine from stalling during demanding manoeuvres. The close interaction between the RCS and the ECS is fundamental for a CPP to ensure adequate load reserve for engine acceleration without sacrificing the performance of the propulsion system.

The key for an optimal performance is a dynamic adjustment of the propeller pitch depending on:

- the actual engine speed;
- the requested propulsion demand;
- the available engine load reserve.

The load reserve considered within MTU's RCS does not only refer to the static MCR curve, but also considers all potential power reductions, such as active power reductions as result of an engine protection. A typical setting is pitch reduction active if the load reserve is <5 per cent. Reduction of fuel costs by shifting the operating points to areas of higher fuel efficiency is another attractive benefit of variable pitch propellers. This, however, can only be fully explored if a sufficient safety margin is retained, to avoid the areas where propeller cavitation may occur, and if advanced CPP control systems with load control are utilised.

Fi-fi operating modes

Installing a fire-fighting pump at the free end of the main engine crankshaft will save installation costs and space. But to safely manoeuvre the tug in a fi-fi mode requires a propeller speed control independent from the engine speed. This can be achieved either by CPP propulsors or FP propellers in combination with slipping clutches, such as the Twin Disc marine control drive (MCD).

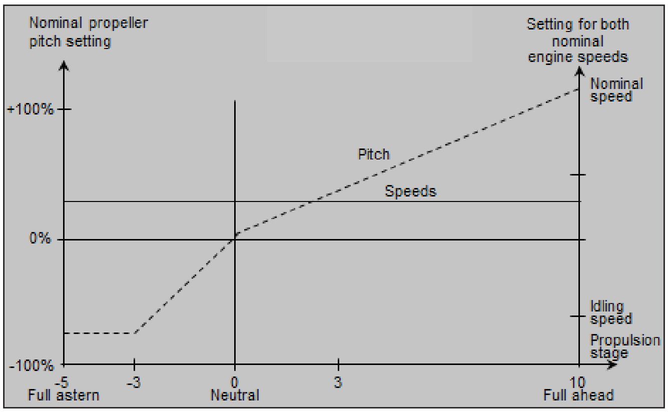


Figure 25: Example fi-fi combinator curve

With CPP propulsors, a 'fi-fi mode' function offers an engine speed selection at the requested fi-fi pump flow rate, while the RCS lever only controls the propeller pitch. *Figure 25, previous page*, shows a typical CPP combinator curve with constant engine speed.

CONCLUSION

When MTU installed electronic displays into one of its original control stands at the beginning of the 1980s, customer feedback was devastating. None of any crew accepted the looks or the function because the design was so unusual for a ship's engine room. The devices were all designed with the best intentions, but counterintuitive for trained seamen. Such reactions from the people who have to work in the maritime environment had to be taken seriously, so MTU put a lot of effort into adapting modern devices to the requirements of crews.

In general, this principle must be respected with all new developments. In the end, it is the people who have to work with new inventions that we need to consider. Risks can be added into a system by applying too much automation, because people may become induced into inaction and their jobs rendered too uninteresting.

There is a fine line between exaggeration of the benefits of automation and equipping a vessel with reasonable features that do not influence the job of the crew negatively. One very practical feature is an equipment health monitoring system (EHM).

The idea behind this is to analyse the huge amount of collected data to detect component failures at an early stage. This proactive service approach helps to reduce unplanned maintenance, which is usually very expensive. Analysis of minimal deviations from normal conditions cannot be performed by humans, and therefore requires powerful electronic tools. This kind of data analytics technology is already working in the aerospace business and the offshore thrusters of Rolls-Royce, and is currently being adapted to work on MTU marine engines.

REFERENCES

[1] Reproduction from *Wissensspeicher für die Berufsausbildung-Verbrennungsmotoren*, Transpress Verlag, Berlin 1974 VLN 162, 925/75/74, PD-Schöpfungshöhe. Taken from https://de.wikipedia.org/w/index.php?curid=8197521

[2] Hunt E, A letter to the journal *The Engineer* (London), 20 Feb 1858. Taken from https://www.linkedin.com/pulse/story-governors-pengju-kang, 3 March 2017

[3] Segbers D, Stöckle P, *Optimising the Total Cost of Ownership by Customised Maintenance Concepts*, ITS 2014

[4] Dr Ihmor S, Müller C, *Monitoring and Remote Control for MTU Ship Propulsion Systems*, MTU Whitepaper, January 2014