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Design

Coordination of FPSO and Tanker Offloading Operations

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Introduction

There is no argument that the effects of control and automation technology on the marine transportation industry have been great. Since the invention of the first autopilot by Sperry early in the last century, we have seen the invention, innovation and improvement in new control technology, culminating in today’s heavily automated vessels. Control and automation technologies, specifically Dynamic Positioning (DP), have benefited the industry by enabling vessels to do things that would not have otherwise been possible using manual methods.

This paper looks at the application of intelligent or knowledge-based control (IC or KBC) technology to the control of marine vessels. The next section gives the motivation behind IC and how it differs from classical control systems theory. The following section discusses how marine vessel control can benefit from the application of IC, with the example of an FPSO and an offloading tanker operation. Finally, the current progress with regards to the proving of this concept using model testing and simulation is given.

Intelligent Control Technology

Traditionally, control systems are thought of in terms of controlling single or multiple variables in a continuous way through various control algorithms; i.e. PID, LQ, etc. The designer or implementer has to consider the stability and efficiency (optimality) of the system as he deploys it. Some sort of numerical model is usually developed to capture the dynamical behavior of the

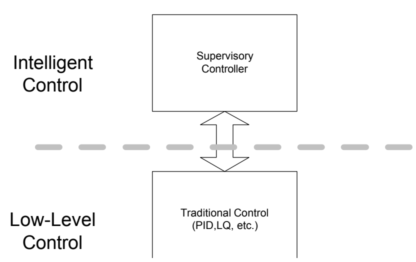
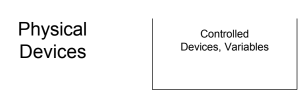


Figure 1: Intelligent control structure



controlled system (plant). These technologies are very well developed and understood. Improvements to these control techniques are at best incremental. The weakness of traditional control techniques is primarily in fault tolerance, reconfigurability and recovery, areas where intelligent control is particularly strong. Often, a human operator carries out the topmost level of this hierarchy, the intelligent control function (see Figure 1).

Increasing System Complexity

Arguably, it can be said that the control systems world is going through a revolution at this time, as research shifts away from classical continuous control and towards the areas of intelligent control technologies as ways of managing and controlling large systems.

With the proliferation of embedded systems and cheap digital hardware, control becomes cheaper and easier to deploy in large-scale systems. The challenge is to develop new control techniques to harness the power of such systems safely and to achieve the overall goals effectively. In a large-scale system ideally, traditional control techniques take care of the low-level continuous control tasks, while a layer of intelligent control coordinates the logical (also known as discrete-event) aspects of the many controlled subsystems. The IC control hierarchy is diagrammed in Figure 1.

Operator, Designer Overload

Human operators are currently being relied upon to serve as the coordination (or intelligent) layer in large, complex systems. Better training for operators is an interim solution, but as systems become more complex, we believe that the operator's ability to *reliably* diagnose and react to problems will become a major stumbling block in the future development and deployment of advanced marine systems. Designing controllers for such large systems is becoming more and more difficult, and human error can be inserted into a control system at the design stage, during training or even maintenance.

It is clear that new tools need to be developed for designers to use when developing control systems for such large-scale systems. This is currently the focus of many research teams active in diverse industrial areas, including manufacturing, highway traffic systems, aircraft control, mining, and telecommunications.

If a system is constructed from multiple subsystems, it becomes more complex due to the interaction of these sub-components; this is known as *interactive complexity*, and it can present a major challenge to designers as well as operators. Take for example the simple system in Figure 2 for which a controller might be designed. A discrete model of the generators' functionality is represented by the two graphs (finite state machines). The two generators (N=2) represent subsystems within a vessel power system. Each generator has three (n=3) *states*; i.e. running (RUN), stopped (STOP), or down (DN). The states are connected by *events* that may be

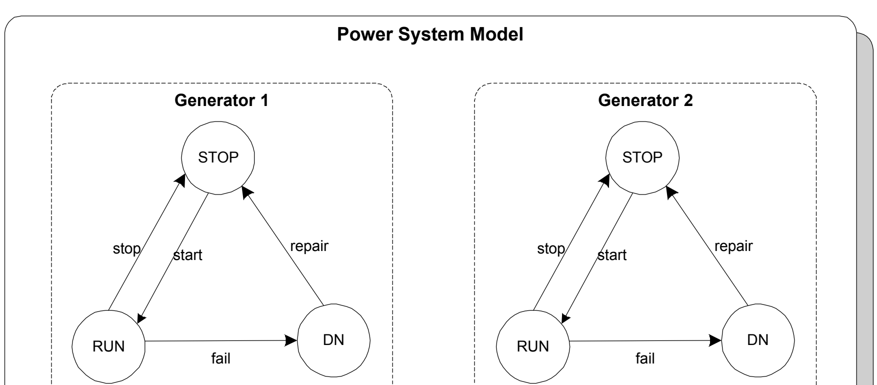


Figure 2: A simple discrete-event model of a two-generator system.

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controlled (*start*, *stop* and *repair*) by the controller and one event (*fail*) that can't be controlled since it occurs spontaneously. The controller is able to observe all events. The whole system when considered together actually has n^2, or 9 states (tabulated in Table 1). The system complexity increases dramatically if we include additional subsystems, each having interconnected states and actions. In general, the complexity increases by the N^{th} power (where N is the number of interconnected subsystems) if there are no shared common events between systems. For example, if another generator were to be added, the number of total system states becomes $3^3 = 27$. Some of the combinations of these subsystem states may lead to undesirable consequences and we would like to design a controller that can prevent the system from reaching this state. If the system is very complex (i.e. on the order of 10^5 or more states), the control system designer or operator may simply be unable to identify these undesirable states due to the "needle in a haystack" nature of the problem.

System State #	Generator 1 State	Generator 2 state
1.	STOP	STOP
2.	STOP	RUN
3.	STOP	DN
4.	RUN	STOP
5.	RUN	RUN
6.	RUN	DN
7.	DN	STOP
8.	DN	RUN
9.	DN	DN

Table 1: All possible states of the simple 2-generator system

Intelligent Supervisory Control

A supervisory controller is one that monitors and controls the behavior of other, subordinate control systems. It serves in a coordinating role, since it is not concerned with the goals of the individual subordinate control systems, but with the overall goals of the entire system. Methods have been developed to synthesize supervisory controllers that incorporate knowledge of the logical (discrete event) structure of the controlled subsystems.

Correct by Design

Lets take a look at our simple system of the two generators outlined earlier (depicted in Figure 2), and look at how a controller could be designed. Let's assume that the goal of the system is, for example, to avoid the situation in which both generators are in the down state (State #9). As stated before, Table 1 itemizes all of the possible states of the system. We have a supervisory controller that does not actively force events to occur, but prevents or disables events from happening. Since failure of a generator is a spontaneous (uncontrollable) event, the controller cannot prevent it, and if both generators are running at the same time, it is possible that they could both fail. We need to prevent the system from entering states from which a *fail* event takes the system to (DN, DN). This means also that the controller must prevent a 'good' generator from starting if the other is being repaired (DN), in case the remaining generator fails. This seems to be an inane solution, since we are prevented from using a working generator while another is being repaired, but it is the literally "correct" solution, given the design requirement. If this were a safety-critical system, it may be necessary to enforce such a control policy.

We arrived at a control solution to this problem by a 'seat of the pants' system examination, but this same process can be automated for very large controlled systems. It is this automated controller synthesis that is most useful to the controls designer. A computer can exhaustively search all possible system states, in order to identify and avoid illegal or unsafe conditions.

As an additional note, the undesirable behavior of this system was specified as a particular state; alternatively, we could have specified a set of events that we wish to avoid (or alternatively enforce). For example, we may wish to prevent generator 1 from executing a start/stop sequence more than three times; i.e. we would disallow the sequence of events {*start, stop, start, stop, start, stop).*

Centralized or Decentralized Implementation

Intelligent or coordinating control can be either centralized or distributed (decentralized),

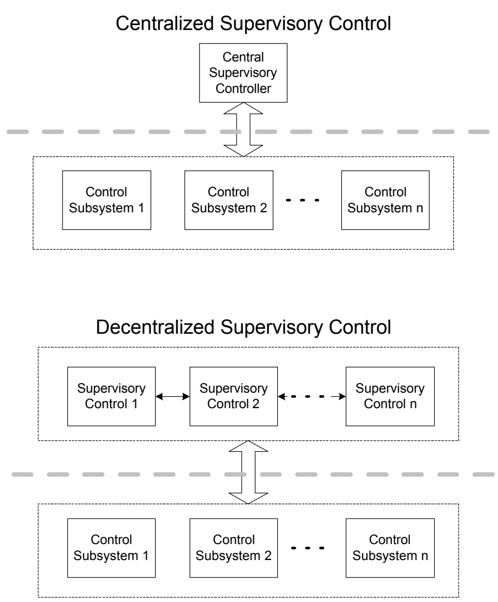

Figure 3: Centralized vs. Decentralized supervisory control

diagrammed in Figure 3. In the case of the centralized control, the controller must be able to observe the entire subsystem it is controlling, while in decentralized control, controllers are distributed around the entire system, and through some sort of information sharing scheme, can act in a coordinated way to achieve a greater good. Automated methods of generating a controller can be applied to both the centralized and decentralized cases.

Adding Timing

This section has considered a very simplistic system model in which we considered modeling and controlling only the logical behavior of the system. There are methods available for capturing timing information as well, at the cost of increased complexity. If we add timing information to the simple two generator problem, the time required to start the generators could be taken into account and specification for safety could be more specific; i.e. "the two generators must not run together for more than 10 minutes".

Intelligent Control in Marine Applications

Multi-Vessel Control

There are many marine operations that may require multiple vessels to work closely together, including pipe-laying, drilling and offshore production. These types of operations place a high demand for reliability and performance on their DP systems. With the increasing automation of on-board systems, the effect on reliability of the DP system is no longer just limited to the traditional component failures such as wind sensors, thrusters, or DP computers. Related systems, particularly the power generation, distribution and switching have become an important factor in the reliability of DP vessels. Since these systems "communicate" through a common power

Figure 4: Terra Nova FPSO offloading to shuttle tanker offshore Newfoundland

demand on the power buss, other systems on board a vessel (In the case of an FPSO for example) such as gas injection and other oil-related production processes may affect the ability of a vessel to keep station. One such multi-vessel system is the Terra Nova FPSO (see Figure 4) that is currently operating off the East Coast of Canada in the harsh North Atlantic environment.

Similarity to Industrial Automation

A drillship or FPSO is like a manufacturing operation in a factory, since it encompasses many similar industrial processes. The same automation techniques that have been used for logical scheduling of processes and work in factories can be applied to vessel control. A multi-vessel system is of equal applicability, since we have added complexity by the addition of a second vessel to the control problem. The moves that the DP operators command of vessels in a multi-vessel system can be compared to the instructions issued to a factory robot, each having its own task, the completion of which contributes to the overall goal of the factory. For example, an offloading tanker and FPSO can be instructed by the coordinating controller to make a weathervaning maneuver together. Currently, such maneuvers are orchestrated manually by the vessel operators using procedures outlined in a Joint Operations Manual (JOM). The point of an intelligent control system is to either replace the operators' manual instructions by automatically moving the vessel, or to at least assist the operator to perform the maneuver. A controller of this type is likely to do a better job than the human operators for several reasons:

- **Complexity**: the controller has been designed with the structure and dynamics of the entire system. Complex interactions between various subsystems are already embodied in the controller
- **Safety**: the controller is safe by design, since all of the possible scenarios for failure have been pre-computed and the controller knows how to prevent these unsafe conditions.
- **Repeatability**: human operators are affected by lack of sleep, illness, emotions, etc. An automatic control system always maintains the same level of performance.

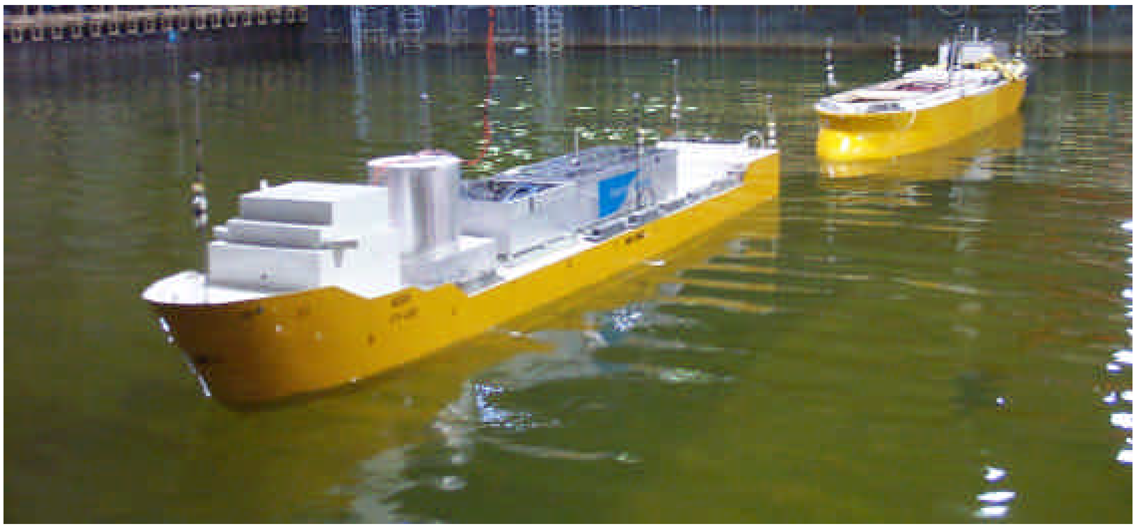

Figure 5: Model test of DP controlled FPSO and offloading tanker.

Redundancy

Currently, redundancy is viewed as the most effective way of improving reliability in safety-critical operations. Redundancy as implemented in DPS-2 and DPS-3 (American Bureau of Shipping designations), mandates that multiple pieces of hardware be operated in parallel in order to mitigate the likelihood of a total system failure due to the single-point failure of one subsystem. Such a scheme is relatively effective for hardware, but the same does not ring true for software based systems, since software doesn't "fail" in the same sense as does hardware; it either works or not. The system reliability of a DPS-3 system lies in the redundancy of the hardware, not the software. Three "redundant" computer programs executing on three correctly functioning hardware platforms, when presented with the same bad input, will each generate the same bad output. Software is not subject to failure or wear-out like hardware is. The problem with this situation lies in the correctness of the software. The lesson from this is that redundancy is not the only measure that can be taken to ensure safety of a system, and techniques such as intelligent control may even enhance the functionality (reliability) that redundant hardware imparts on a system. Failures will occur in a system, and they must be dealt with in the correct way

Role of Model Testing

While many studies can be conducted using numerical models of vessels, it is important to independently verify that control systems work. One such way is to use a physical model since it is much less expensive to implement and operate and the risk of harming real vessels or personnel are low. Secondly, testing model vessels allows us to identify the most challenging conditions for a vessel control system, in a safe and controlled environment; i.e. a wave basin. Since we have ultimate control on the weather, ballast, and even damage conditions, many different scenarios can be accurately modeled and tested.

Model tests were conducted in August 2001, using a full model of an FPSO and offloading tanker at the National research Council's Offshore Engineering Basin (OEB) located at the Institute for Marine Dynamics in St. John's, Newfoundland, Canada. The model scale used for the testing was 1:40, so each of the models is around 7.5 m (25 feet) long. With this large a scale factor, our modeling is very accurate, since scaling effects are minimized. Both models were equipped with fully functioning DP systems employing azimuthing thrusters. While the FPSO is moored, it relies on its DP system to change heading and to provide some surge damping. The tanker model was completely un-tethered and able to move throughout the basin. We were able to explore various scenarios using these model vessels including:

- **Tanker Approaches**: tanker approaches from several boat lengths away to take up station to the rear of the FPSO.
- **Weathervaning:** both vessels moved through various heading angle changes with respect to the sea and current directions. Weathervaning maneuvers were performed with the tanker automatically controlled in follow-mode.
- **Station Keeping:** at various headings, sea states and current directions

These tests served as a means of identifying the most challenging conditions for the tanker/FPSO system from an environmental and operational standpoint. A supervisory controller was not tested since most of the benefits of such a controller are in the coordination of the many control systems on board each vessel (including the DP systems), and in the fault recovery. Final proof of concept for the controller will be tested in a model test early next year. Another important part of the testing will be simulations, using real data from an operating FPSO and shuttle tanker as an input to the simulated controller.

Conclusions

Intelligent Control methods are being developed to deal with the increasing complexity and decentralization of various industrial processes. Due to the magnitude of today's controlled systems, it is becoming increasingly difficult for traditional design checks such as design reviews, simulations and testing to find flaws in a system. How can the designer be sure, that the tests conducted have found the hidden flaw (i.e. some interaction between subsystems that was overlooked)?

The marine industry is likely to be one other area that can benefit by the application of intelligent control technologies. One method for constructing an intelligent controller that is “correct by design” is to incorporate a model of the logical behavior of the system to be supervised, along with the designer’s specifications for safety and correct operation. This approach works because all of the possible logical combinations of the various subsystems can be exhaustively evaluated ahead of time in order to identify all possible outcomes that are either unsafe or not useful. With this knowledge, the controller is able to prevent the system from approaching these dangerous conditions by intervening before they occur.

Automated design methods currently exist to implement an intelligent controller to supervise and coordinate safety-critical application such as DP positioned vessels. These methods show great promise, but are currently too cumbersome to implement in most industrial control systems for various reasons. The development of new software tools and training for control system designers will be necessary before there is wide-scale acceptance of this technology by industry.

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