Using bond graphs for identifying and analyzing technical and operational hazards in complex systems

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Abstract: Oil and gas exploration and production is moving into harsher environments, such as the Arctic, which increases the complexity of operations. Technology development introduces more advanced functionality and operators may not have the full overview or knowledge to handle deviations that propagate in the systems. The increasing complexity and couplings in systems and operations means that a systems approach is necessary to ensure sufficient risk management for accident prevention. Current risk analysis methods, however, have limitations. This paper investigates the use of bond graphs as a systemic method for analyzing risk in dynamic systems, for example, as a supplement to hazard and operability analysis (HAZOP) and system theoretic process analysis (STPA). The article uses a remote operated vehicle (ROV) for subsea operation as a case study.

Keywords: Risk assessment, Systems theory, Bond graphs, Remote operated vehicle (ROV)

1. INTRODUCTION

Exploration and production of oil and gas resources is moving into harsher environments, such as the Arctic. To obtain permission to start up and operate oil and gas installations in Arctic areas it is necessary to focus resources specifically on preventing accidents and damages to human beings and the environment. Even though this is already very important in the North Sea having sufficient and significant risk management systems in place for accident prevention in Arctic areas will become increasingly important [1-2].

Technology is changing faster than ever and the time to market for new solutions is decreasing. Complexity is increasing in the new systems, particularly in terms of coupling between sub-systems and components. These couplings may be very difficult to understand during planning and design. In addition, operation and the surroundings may be so complex and demanding that most operators do not have the full overview of potential behavior of the systems, and may not have the ability to handle all arising situations and disturbances safely.

The added complexity of systems and challenges related to their operating surroundings put increased demands on risk analysis as input to decision-making for both industry and authorities. Current risk analysis methods are feasible for addressing technical risk, whereas integration of operational risk remains a challenge [3]. Human operators and their role with respect to safety have traditionally been simplified. As systems become more technological advanced and complex, operators increasingly assume supervisory roles over automation, which requires cognitively complex decision-making where mistakes can no longer be effectively considered as simple random failures. The design of systems today leads to new types of operator errors, such as confusion and lack of situation awareness. Accidents occur due to interactions among system components and are not a result of one single failure [4].

According to [4], safety is controlled or enforced in terms of constraints on the system behavior. Hence, safety can be considered a control problem and accidents happen when safety is not controlled sufficiently. Hazardous events reflect inadequate control, for example, in the design process or during operation. As such, the control structure has to be understood in order to gain understanding of what went wrong in an accident. Enforcing control in terms of safety constraints on component behavior can

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be performed through design, production or the maintenance process, or through social controls, such as management, regulations, culture or societal, and policies.

Hazard and operability analysis (HAZOP) is a method for risk analysis commonly used during the design process, both before commissioning of the system and during modification of an existing system [5]. [4] states that there is a need for “new types of hazard analyses and risk assessments that go beyond component failures and can deal with the complex role software and humans are assuming in high-tech systems”. The basis for such new methods should be constituted by systems theory. Systems theory assumes that some systems cannot be separated into subsystems without losing information about systems’ interactions and the relationships between technology and social aspects. The system theoretic process analysis (STPA) is a recently proposed risk analysis method based on systems theory, with some similarities to HAZOP, but it focuses more on system functions and control [4].

In the systems approach understanding functions is decisive, which can be facilitated through system modeling, especially for systems whose behavior as a function of time is important. Hazardous events imply that systems are in a deviating state reaching or transgressing the limits of its operating envelope. Hence, dynamic system analysis for hazard identification and analysis, even though it is resource demanding, seems preferable compared to assuming steady state and constant system performance.

The bond graph language is a common conceptual and operational framework for the analysis of a very wide variety of system types. Bond graphs is proven an efficient methodology for modeling of especially hybrid dynamic systems. Advantages are that the same use of symbolism can represent power interaction in a large selection of physical systems, and causality can be shown in terms of input and output variables. In the method of bond graphs it is possible to separate and concentrate properties of a component and then describe it as a system of interconnected basic ideal elements. Hence, it is possible to predict the behavior of systems with an acceptable limit of accuracy [6]. Bond graphs may contribute to improved knowledge about systems, including impacts from human operators, and hence possibly reveal additional hazards than those identified and analyzed in traditional risk analysis.

The objective of this paper is to investigate the use of bond-graphs as part of a systemic approach for assessing technical and operational hazards in complex systems for challenging environments. There is hardly any research on application of bond graphs for use in risk analysis. One exception is [7] who uses bond graphs to analyze disturbance paths and compares with fault tree analysis (FTA). The current paper introduces bond graphs as means for providing useful input to risk analysis, and specifically for HAZOP and STPA. A case study illustrates the approach focusing on subsea operations and a remote operated vehicle (ROV). ROVs are increasingly used and their development towards more autonomy is especially desirable with the expansion of industrial activities in the Arctic [8].

The structure of the paper is as follows: Section 2 briefly presents the risk analysis methods HAZOP and STPA. Bond graphs is introduced in Section 3 and Section 4 illustrates how bond graphs may be integrated into risk analysis through a case study on ROVs, providing additional information concerning operational hazards. Last, conclusions are given.

2. RISK ANALYSIS

2.1. HAZOP

HAZOP considers the purpose of a system, operational modes, and possible deviations during the modes. Causes to any deviations, possible consequences, and the need for risk-reducing measures are considered. HAZOP typically starts with dividing the system into study nodes that are analyzed one by one. Physical component diagrams, such as a piping and instrument diagram (P&ID), are used for understanding the system and separating the study nodes. Various guidewords, shown in Table 1, are used to analyze deviations in operation and any hazards that these deviations may cause. Existing safeguards or barriers are evaluated and a decision is made about the need to follow up and implement improvements. In some cases, more detailed analysis about the risk may be required [5]. When all study nodes have been considered, the guidewords should be used for reviewing the whole system [9].

Currently, HAZOP studies are used in many different industries, and have become a standard activity in the design of the process systems on offshore oil and gas platforms in the North Sea. Initially HAZOP was developed for use in the design phase, but may also be applied to systems in operation [5].

Table 1. Typical generic HAZOP guidewords, adapted from [5, 10-12].

Guideword	Property	Deviation (examples)
No/none	Flow	No flow
Less	Pressure	Less pressure
More	Temperature	High temperature
Reverse/opposite	Time	Delayed control
Threshold	Level	Insufficient communication
Insufficient	Control and monitoring	As well as composition – high concentration of impurities
Faster	Communication	…
Slower	Cleaning and emptying	
High	Function	
Low	Particles/composition:	
Early	• Properties, e.g., viscosity, sand, concentration, reactions, impurities, corrosion materials	
Late/delay		
Malfunction		
Before	Junctions and couplings:	
After	• Drainage, ventilation, auxilliary systems	
Other than		
Part of	Health, Safety, Environment:	
As well as	• Explosive gases, toxicity, leakages rotating parts, pressure relief, environmental impacts	
	Interface/instruments:	
	• Signal/data processing, capacity, prosess control	
	Maintenance:	
	• Access, isolation	
	Operation mode:	
	• Start-up, stop, shutdown, breakdown, emergency stop	
	Other:	
	• Deviations in drawings, notes	

2.2. System Theoretic Process Analysis (STPA)

STPA was introduced by [4]. Similarly to HAZOP, STPA uses guidewords to assist the analysis, but a functional diagram is used, rather than a physical diagram. The focus is on identifying and analyzing hazards to mitigate or reduce risk in design and operations. In general, an unsafe control action may be unsafe if (i) it creates a hazard, (ii) a required control action is not provided, (iii) it is provided too late, too early or in wrong order, (iv) it is provided too long or stopped too soon, and (v) it is provided, but not followed.

A hierarchical safety control structure includes higher-level controls, such as safety policy, standards and procedures, and lower-level controllers that implement theses. Between each level there is a feed back control loop that provides learning and a possibility to improve effectiveness of the safety controls. Every controller has an algorithm for deciding what control actions to provide, which uses a model of the current system state to help making the decision. This means that the controller issues control actions to alter the state of the controlled process based on assigned requirements that ensure that safety constraints are maintained. For a human controller the process model is a mental model.

STPA has two main steps [4]:

1) Identify potential for inadequate control and hazardous control action
2) Determine how each potentially hazardous control action identified in Step 1 may occur

The causal factors can be related to three general categories; (i) the controller operation, (ii) the behavior of actuators and controlled processes, and (iii) the communication and coordination among controllers and decision – makers. Input to controllers may be wrong; algorithms (procedures for hardware or human operators) can be wrongly implemented. Further, time delays must be considered, and insufficient process models may lead to unsafe actions. Multiple controllers need coordination and responsibilities must be defined [4].

Supervising an automated system requires extra training and skill of a human operator, and not the opposite as sometimes is assumed. Human controllers need additional information not only about the process they are directly controlling, but also of processes they control indirectly. Hence, hazard analysis has to identify the specific human behavior that causes hazards. Humans will update their control algorithms according to goals and feedback [4].

STPA is a qualitative risk analysis method, as it does not quantify probabilities to avoid omitting important causal factors for which probabilistic information does not exist. It is a top-down method, which means that the initial list of hazards should be small and at an overall level, i.e., contain less than 20 and preferably less than 10. When the high level system hazards have been identified safety requirements or constraints have to be derived. At this point the system control structure (which is not part of the STPA method) is needed to perform STPA, reflecting the functional design of the system. The control loop (controlled process, sensor, controller, actuators) has to be examined to see if they contribute to hazards and as details may be added, such as responsibilities, the control actions, and feedback, the control structure is refined and expanded [4].

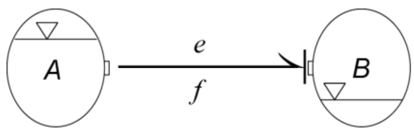
Bond graphs can be used to model any energy dynamic system and are easily connected to control systems using standard block diagram representation. Hence, it may work as a functional diagram. The bond graph method can be said to represent an object-oriented approach to mathematical modeling.

3. BOND GRAPHS

The bond graph method is methodology for modeling of dynamic systems based on energy flow, i.e. deriving mathematical state space equations for a dynamic system. The method, originally invented by [13] and brought into diverse applications by [6] is a graphical visualization of the energy flow, storage and dissipation of interacting dynamic systems. The bond graph method introduces a unified approach to modeling and is widely recognized as a powerful approach for mathematical modeling of engineering systems combining mechanical, electric, hydraulic, pneumatic, magnetics, chemical and electrochemical physics, i.e., strongly supporting a mechatronic approach.

The flow of energy between two systems are defined using two basic elements of the bond graph language; i.e., ports and power bonds. The ports represent energy points where there is energetic interaction between systems or a system and its surroundings. The power bonds represent the power flow between two systems. There is no loss of power along the power bond. The bonds can be included with a half arrow on one end, indicating the direction of power flow when it is positive. A full arrow on a bond is called an active bond and indicates a signal flow at very low power [6] and is often used to link the power system to control actions or events.

Figure 1. Power bond visualizing the energy flow.



It is possible to predict the behavior of any energetic system knowing the energy level at each system, i.e., the potential or effort, and the energy flow between each system, i.e., the rate or flow, as visualized in Figure 1. Only four variables are needed to represent the dynamics of physical systems, i.e., the power variables e, f and the energy variables p, q. Effort is represented by e, flow by f, the generalized momentum by p, and q is the generalized displacement. A bond graph can represent the variables effort $e(t)$ and flow $f(t)$, for example for mechanical systems, force and velocity can be considered as $e(t)$ and $f(t)$, which multiplied represent power

$$P(t) = e(t) \cdot f(t) \tag{1}$$

The generalized momentum for a system can be defined as the time integral of effort

$$p(t) = \int_0^t e(t)dt + p(0) \tag{2}$$

where $p(0)$ is the initial generalized momentum at $t = 0$.

The generalized displacement can be defined as the time integral of flow

$$q(t) = \int_0^t f(t)dt + q(0) \tag{3}$$

where $q(0)$ is the initial generalized displacement at $t = 0$.

Setting up a mathematical model using the bond graph approach is often supported following simple procedures in most disciplines [6]. Table 2 shows corresponding energy domains and power- and energy variables [6].

Table 2. Variables and energy domains in bond graph modelling [6].

Energy domain	**Effort**	**Flow**	**Momentum**	**Displacement**
Electrical	Voltage [V]	Current [A]	Flux linkage [Vs]	Charge [As] or [C]
Mechanical translation	Force [N]	Velocity [m/s]	Linear momentum [kgm/s]	Distance [m]
Mechanical rotation	Torque [Nm]	Angular velocity [rad/s]	Angular momentum [Nms]	Angle [rad]
Hydraulic	Pressure [Pa]	Volume flow rate [m^3/s]	Pressure momentum [N/m^2s]	Volume [m^3]
Thermal	Temperature [K]	Entropy flow [J/s]	N/A	Entropy [J]
Magnetic	Magneto-motive force [A]	Flux rate [Wb/s]	N/A	Flux [Wb]
Chemical	Chemical potential [J/mol]	Rate of reaction [mol/s]	N/A	Advancement of reaction [mol]

There are nine basic bond graph elements, shown in Table 3, which can be used to represent the energetic structure of the system. The elements are characterized by the number of energy ports they have (1-port, multiports) and by how they handle the energy. In the bond graph language the effort variable e is written above or to the left of a bond, whereas the flow f variable is put below or to the right of the variable [6].

Basic 1-port elements represent energy supply, storage and dissipation. To model energy supply to a system, energy sources are needed. An energy source provides power continuously by an external energy reservoir to the system. Two idealized sources are defined, i.e., source of effort S_e, and source of flow, S_f. An ideal effort source is capable of providing enough effort on the system regardless of flow, and vice versa for the ideal flow source [6].

Most systems store energy either in the form of potential energy or kinetic energy. This can be represented by 1-port capacitor element or a 1-port inertia element. The capacitor element uses the mnemonic code C and can generally be defined as $q = \Phi_c(e)$. In the linear case it can we written $q = C \cdot e$ where C is the constant capacitance parameter. The capacitator element is the idealization of physical components, such as springs, capacitors, and liquid storage tanks [6].

The energy stored in a capacitor element at any time t can be represented by

$$E(t) = \int_0^t (e \cdot f)dt + E(0) \qquad (4)$$

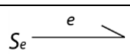
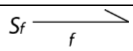
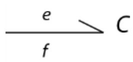
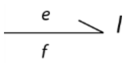
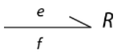
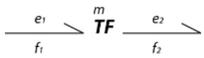
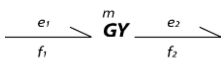
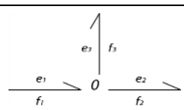
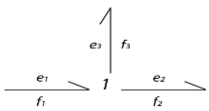
where $E(0)$ is the initial stored energy at $t = 0$.

The inertia element uses the mnemonic code I and the corresponding constitutive law can be defined as $p = \Phi_I(f)$. In the linear case this can we written $p = I \cdot f$, where I is the constant inertia parameter. The inertia element is an idealization of physical objects, such as mass or inertias, inductance in electrical systems or inertia effects in hydraulic systems.

Power dissipation, energy lost from the system as a function of internal relations between effort and flows, is handled by the 1-port resistor element. The resistor element uses the mnemonic code R and is characterized by a static relationship between e and f: $e = \Phi_R(f)$ in the general case and $e = R \cdot f$ in the linear case where R is called the constant resistance parameter. The R-element is used to model all types of energy dissipation, such as mechanical and hydraulic friction and electrical resistors [6].

Two-port elements are the transformer element (*TF*) and the gyrator element (*GY*). Both elements transmits power through the system without any loss or accumulation. The former relates an effort on one port into an effort on the other port with a magnitude depending on the modulus, displayed on the graph above the *TF*. The gyrator relates an effort on one bond into a flow on the other bond with a magnitude depending on the gyrator modulus, displayed above the *GY* [6].

Table 3. Bond graph elements, based on [6].

Name	Bond graph element	Constitutive relationship
Effort source		$e = e(t)$
Flow Source		$f = f(t)$
Capacitance		$\int f(t)dt = \Phi_C(e)$
Inertia		$\int e(t)dt = \Phi_I(f)$
Resistance		$e = \Phi_R(f)$
Transformer		$e_1 = me_2$ $mf_1 = f_2$
Gyrator		$e_1 = f_2 r$ $f_1 r = e_2$
0-junction		$e_1 = e_2 = e_3$ $f_1 - f_2 - f_3 = 0$
1-junction		$f_1 = f_2 = f_3$ $e_1 - e_2 - e_3 = 0$

The system topology is decisive for the arrangement of the elements. There are two types of junction elements, the *0*-junction and *1*-junction, both that is power continuous and routes energy into the appropriate paths without any delay or loss. The *0*-junction has equal effort on all bonds joining while all flows on connected bonds sums to zero and represents Kirchhoff's current law in the electric domain. The *1*-juntion is a multiport element where the flows are equal and all efforts are summed to zero and as such represents Kirchhoff's voltage law [6].

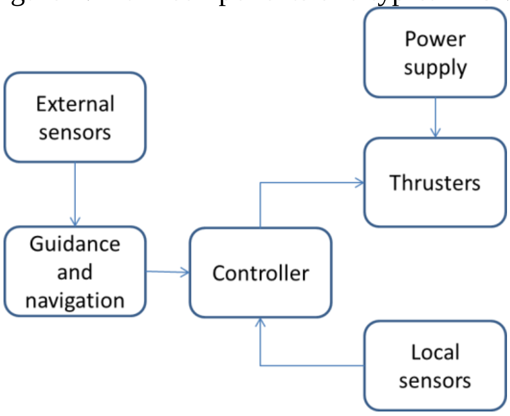
4. CASE STUDY – REMOTE OPERATED VEHICLE (ROV)

Underwater vehicles can be divided into manned submersibles and unmanned underwater vehicles (UUV), i.e., towed vehicles, remotely operated vehicles (ROV), and autonomous underwater vehicles (AUV). An AUV is not directly controlled by an operator, but is mainly pre-programmed for a given mission. The main power source is integrated and communication with an operator is related to data transmission with limited bandwidth. Contrary to a ROV, an AUV has no permanent connection to an operation centre. There is few fully autonomous underwater vehicles; current systems operates by consent which means that the AUV recommends actions to the operator and the system involves the operator at key points for information or decisions [14].

Increased use of ROVs, and eventually AUVs, is required in the Arctic as new areas become accessible for operation [15]. AUVs can provide easier environmental monitoring, mapping and monitoring of ice [16]. Future AUV capabilities will enable inspection of subsea equipment and pipelines in deep-water. In the following, the focus is on ROV systems as these are most common for subsea inspection, maintenance and repair of equipment and infrastructure.

A typical ROV system, shown in Figure 2, is here defined to consist of six main parts; (i) external sensors, (ii) the guidance and navigation system, (iii) the control system, (iv), thrusters, (v) local sensors, and (vi) power supply.

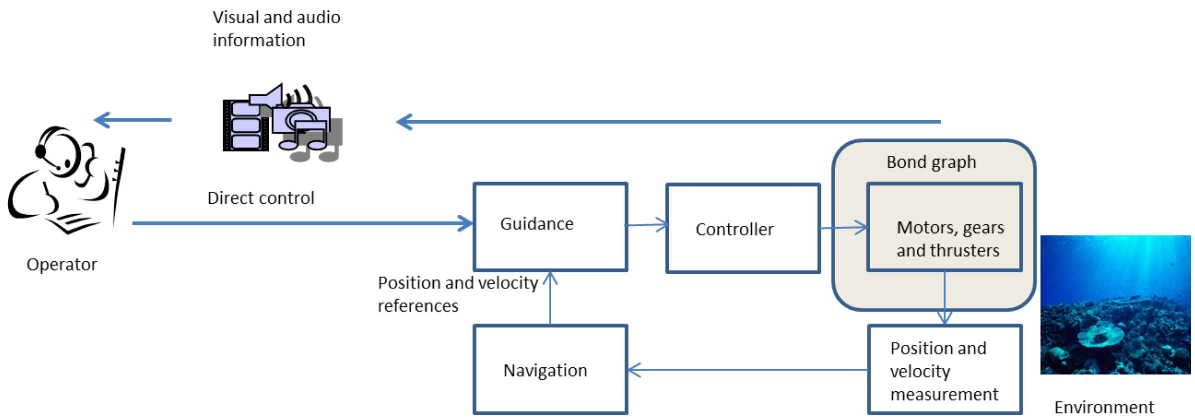
Figure 2. Main components of a typical ROV.



An energy storage system provides the electric power to the motor. The motor supplies mechanical energy to the whole system, i.e., the thrusters, manipulators or tools, the control system/pilot, and the emergency system. The ROV may be equipped with one or several manipulators to carry out different operational functions. The manipulators are usually powered by a hydraulic system connected to the motor and the control system/pilot. The power transmission consists of a gear connected to the motor and the thrusters.

The manoeuvring of the ROV is determined by the control system and/or the operator. The positioning system sends signals to the control system that compares it to pre-set values and mobilizes the propulsion system to minimize the difference. The ROV may have a local control system, i.e., dynamic positioning (DP) system or can be directly controlled by the operator. This is schematically shown in Figure 3.

Figure 3. Control structure of an ROV. The grey box shows the relationship to the bond graph in Figure 4.



The equations of motion of an ROV with one manipulator arm can be written as

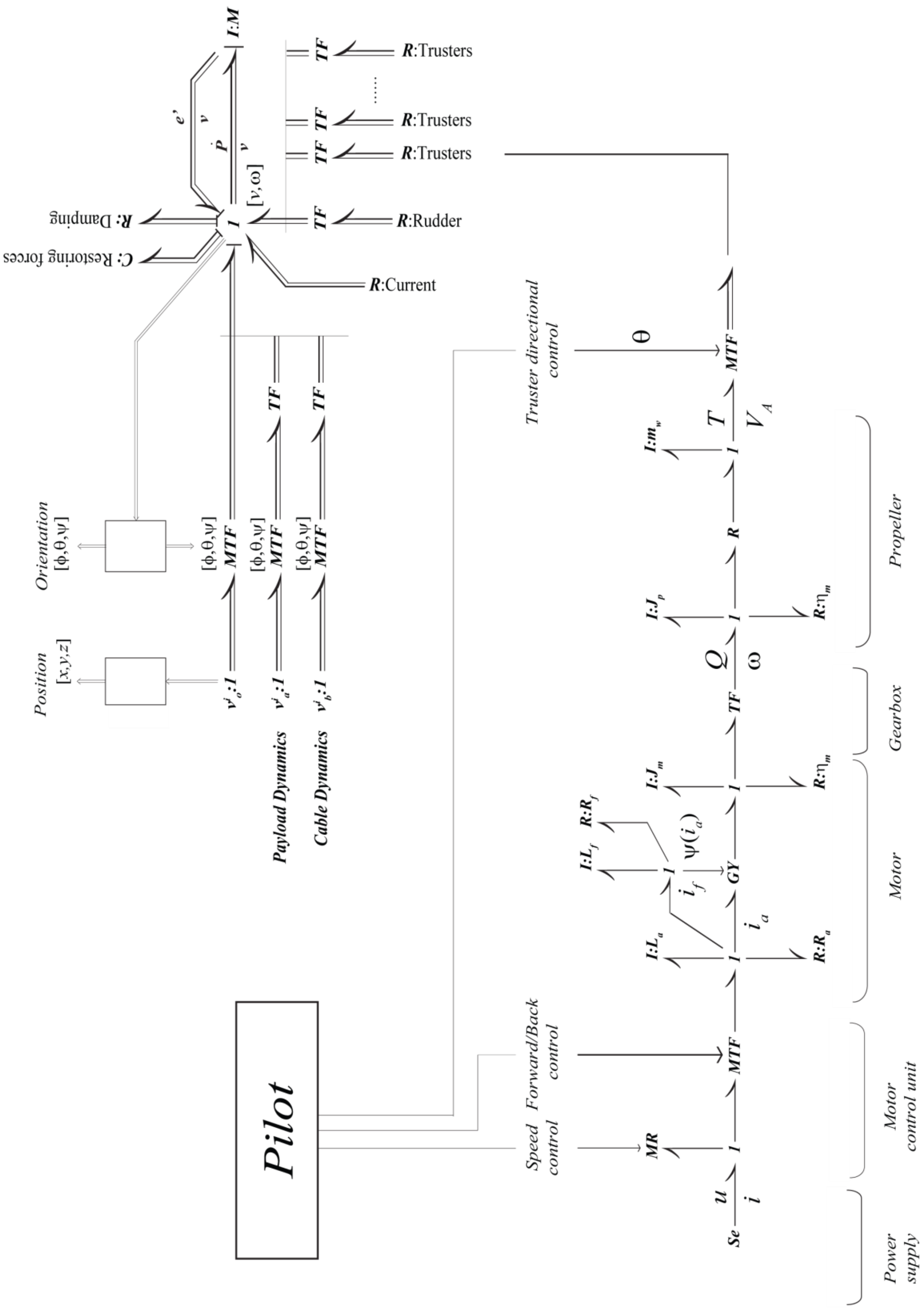
$$M(q)\dot{\varepsilon} + C(q,\varepsilon)\varepsilon + D(q,\varepsilon)\varepsilon + g(q,\theta) = \tau \qquad (5)$$

where q is the joint position of the manipulator arm, ε is the vehicle and manipulator arm velocities ($\dot{\varepsilon}$ is acceleration), and θ is the position and orientation of the vehicle in an inertial frame. M is the mass matrix of the system, C holds the Coriolis and centrifugal terms, D the damping terms and g the gravity terms. Cable dynamics is integrated in this representation, as well as coupling force between vehicle and manipulator. τ is the control input for position, orientation and velocity control [17]. For tracking control a model-based proportional-derivative (PD) controller could be used. The control input is designed to compensate for thruster and motor dynamics.

A bond graph, as shown in Figure 4, can be applied to analyze the energy supply and the functionality of the thruster, gearing and motor system. The mass of the vehicle is described as the inertia with the multiport I-field (I:M), where the translational and angular inertia is represented with corresponding velocities as input. Restoring forces are all forces acting on a vehicle to resist its deviation from its static equilibrium. For an ROV the restoring forces will depend on the location of the centre of gravity and the centre of buoyancy. These forces are efforts in the bond graph model, and can be represented as ideal potential energy accumulation in terms of a *C*-element. Ocean currents are usually modeled by assuming a constant current velocity. Such currents add to additional Coriolis, centripetal and damping forces and are dependent on vehicle velocities. Thruster forces impacting a vessel is a complex relationship between the vehicle´s motion, sea conditions (currents and waves), water flow around the thrusters, the design of the propulsion system and control inputs. The thruster forces can be modelled in terms of a relation between flow and effort, i.e., shown as an *R* element in the bond graph model in Figure 4. The *TF* element represents the rudder forces due to rudder lift and drag forces generated by the position of the rudder relative to the vehicle main body. A detailed model for one of the thruster systems on a ROV is presented by a bond graph in Figure 4, further developed from [18]. The bond graph receives the control input and calculates the energy flow.

The on-board energy and propulsion system is essential for safe operations and bond graphs is one method to analyze disturbance paths and perform HAZOP or STPA on these systems. The graph supplies a simple framework for fault and consequence analysis of the energy and propulsion system and can (e.g., in Matlab) be linked to the vehicle equations of motion (5) to simulate the behaviour of the total system. This cannot be done with physical layout diagrams, such as the simple layout shown in Figure 2 or even with P&ID. Bond graphs may, as such, be considered an advanced expansion for providing input to STPA.

Figure 4. The bond graph model of the ROV.

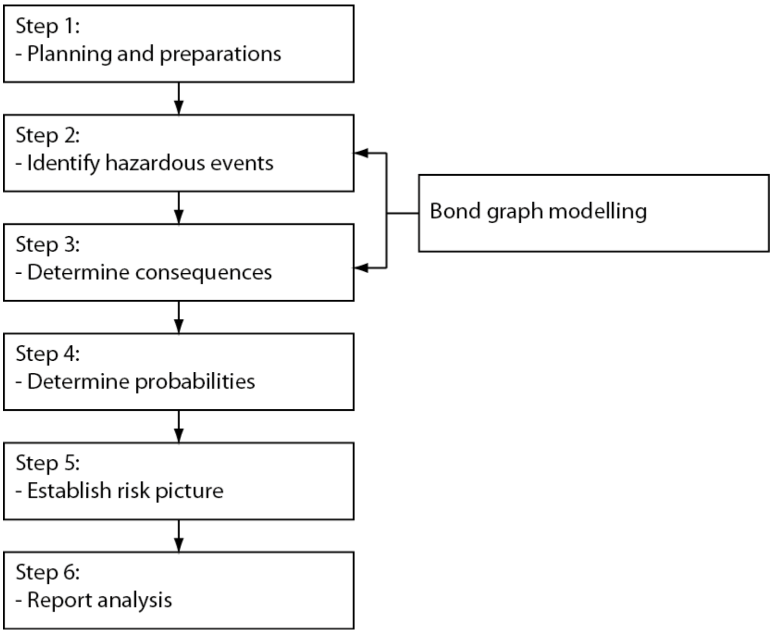


5. DISCUSSION

To design a robust ROV, requirements to product safety, availability, functional safety, and maintainability have to be fulfilled. These requirements must focus on the technical system, as well as the human operator and interaction when manual control and intervention is needed. A producer of a ROV has to establish a systematic way for ensuring that the safety performance requirements or constraints are addressed throughout the system life cycle. This means that feedback or transfer of experience and knowledge between development and operation is crucial.

Bond graphs can be used to simulate system behavior under various circumstances, for example, to analyze different system configurations and/or operating conditions and impact on system performance. The operator´s interaction with the system can be investigated trough the control of the system. This is modeled for the ROV in Figure 3, where the operator controls the speed and position. This means that bond graphs can be used for more detailed and "dynamic" HAZOP analysis. STPA needs a functional diagram rather than a physical diagram, such as a PI&D. Bond graphs can be used to model systems in which the functions of the system and the system control structure can be investigated. This means that several aspects of a system becomes more "visible", such as dynamic forces acting on the system (cf. the motions in Figure 4) and how signals are transmitted through the system in terms of operator interaction and control.

Figure 5. The relationship between bond graph modeling and risk analysis.



HAZOP is effective for technical failures and to some extent human errors, and develops recommendations for additional or modified barriers. The analysis is, however, dependent on the facilitation of the leader and the knowledge of the team and is optimized for process hazards. Hence, it needs modification to cover other types of hazards and requires development of procedural descriptions, which are often not available in appropriate detail [5]. HAZOP analyzes a system or process using a "section by section" approach and may not identify hazards related to interactions between different nodes. The latter implication is becoming more important as couplings between subsystems and components increase. Analysis of component interdependencies can be facilitated by bond graphs and is one of its main advantages.

Typical guidewords in HAZOP, shown in Table 1, can be used for simulating and investigating deviations in the energy flow throughout a bond graph model. A taxonomy, e.g., from [19], can be used as a starting point for the simulations and more detailed analysis for identifying and analyzing hazards.

For example, the consequences of an operator failing to provide the correct input to the ROV by activating the wrong switch can be investigated. [4] claims that one of the main advantages of STPA is that more hazards are identified and using bond graph supports this view. Figure 5 shows where in the risk analysis process bond graphs can provide useful input, i.e., to hazard identification through modeling and simulation of energy flow and deviations and to determine consequences of such deviations on the system and operation.

Bond graphs is based on modules or “building blocks” which means that a system can be modeled relatively efficiently by reuse and reconfiguration of previously built modules. This means that the initial establishment of the bond graph model is relatively resource demanding, but once it is developed, reuse and modifications are less time consuming.

6. CONCLUSION

In this paper bond graph modelling is presented as a method for identifying and analysing hazards in dynamic systems. A bond graph model of a ROV is provided, including a representation of the control system and the operator. Bond graphs is a unified approach to modeling and visualizing the energy flow, and is widely recognized as a powerful approach for mathematical modeling of engineering systems. The complexity of engineering systems increase with the technological development at the same time as operating surroundings become more demanding, such as in the Arctic. Present types of risk analysis methods are feasible for addressing technical risks, but sufficient analysis and integration of human and organizational factors is still a challenge.

A systems approach to safety means that the components of the system have to be considered in relation to the system as a whole, because the system is more than the sum of its parts. A change in one component may have propagating and unpredicted consequences on other parts of the system. Bond graph models are feasible for modeling deviations and cascading consequences, including in the control structure, which means that impact from the human operator is possible to analyze. Hence, bond graphs support the system approach to safety and provides a promising tool for more detailed analysis of hazards in complex systems.

Further research should focus on more complex applications and simulations of dynamic systems for detailed risk analysis.

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