

## OFFSHORE PIPELAY OPERATIONS FROM A CONTROL PERSPECTIVE

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### ABSTRACT

*This paper considers the problem of installing offshore pipelines by means of pipelay vessels from a control perspective. Specifically, the paper is divided into two main parts, where the first part gives a thorough introduction to the fundamentals of pipelay operations and the challenges and possibilities associated with such operations. The second part then suggests how pipelay operations can be further automated by augmenting the manually-operated dynamic positioning (DP) systems of today with sophisticated guidance functionality that may improve operational precision and safety by relying on advanced mathematical models.*

### INTRODUCTION

Offshore pipelines are essential for the transportation of oil and gas, and range from small diameter interfield flowlines to large diameter export lines for transportation from offshore installations to shore and for transportation across oceans between countries. In particular, the use of subsea pipelines represents a safer and more environmentally friendly alternative than surface transportation by tankers [1].

Currently, efforts are being made to locate and retrieve oil and gas resources in increasingly deeper waters, and offshore pipeline technology is constantly developed to keep up with these advances. Hence, the main drives in the offshore pipeline industry today concerns installing pipes at large water depths, and in particular the development of large gas gathering and distribution systems throughout the world, such as, e.g., the Langed

and Independence Trail pipelines.

Dedicated pipelay vessels are used to install offshore pipelines, and the first generation of these vessels consisted of flat-bottomed barges that were operated in shallow waters close to shore. A barge was held in place by an anchor-mooring system placed in a spread formation by anchor handling vessels. The position and orientation of this barge could then be kept to avoid buckling and kinking of the pipe, and the barge moved forward by controlling the anchor-line winches. As pipeline diameters and water depths increased, the barges were replaced by large semi-submersibles to provide stable working conditions in more hostile environments such as the North Sea.

However, positioning by mooring has several disadvantages [2]. The mooring lines radiate from the pipelay vessel in a full circle of directions, such that in congested areas it becomes difficult to place the anchors while keeping clear of existing structures, including the already installed pipe. Deep waters also limit the precision of the positioning due to the mechanical flexibility of the mooring system. Finally, the initial positioning and subsequent relocation of anchors is cumbersome, time consuming, and sensitive to weather conditions and sea states.

Due to such mooring-related constraints, the advantages of *dynamic positioning* (DP) for position control of pipelay vessels was early recognized. A DP vessel has a considerably shorter start-up time, and has the ability to abandon and recover pipelines quickly. The motion control becomes independent of water depth and can operate in congested areas and close to platforms. There is also less mechanical downtime compared to an anchor vessel because the wear and tear on an anchor system is more intense.

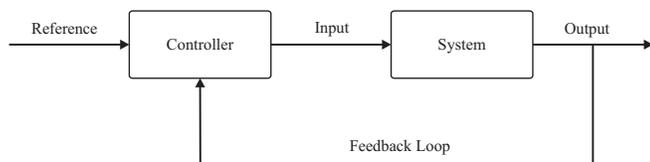


Figure 1. CLOSED-LOOP CONTROL THROUGH FEEDBACK.

The first DP-based pipelay vessel was the Allseas' *Lorelay*, which was introduced in 1985 for deepwater applications [3, 4]. The vessel was ship-shaped, with an aft stinger and large pipe-carrying capability. It quickly proved very successful, particularly in the rough North Sea, and experiences gained from the *Lorelay* was used to construct the largest pipelay vessel currently in operation, the Allseas' *Solitaire* [5].

However, two factors have historically worked against the employment of DP technology, namely the reliability of the system, since system failure potentially causes severe damages to both pipeline and vessel, as well as the power required to balance the tension from the pipe. Still, despite the initial reluctance to use DP systems, all newly commissioned pipelay vessels today are dynamically positioned. To ensure reliability, these vessels are usually configured to IMO Equipment Class 3, with full redundancy in all components.

In practice, a DP operator (DPO) manually controls the DP system based on experience and know-how, using specific features that have been developed to aid in pipelay operations [6]. Such features include *tension compensation*, *pipe-pull* (i.e., move forward one pipe length at a time), and *tracking of vessel path*, where the dynamics of the pipe and environmental loads are compensated for by using a crab angle and track offset. However, the technology implemented in commercial DP systems, including pipelay-specific extensions, is classified and not easily accessible for academic researchers.

Consequently, this paper attempts to give a convenient introduction to and overview of offshore pipelay operations which is suited for control researchers. The paper also looks at the possibility of automating such operations beyond the manual DP-based control procedures of today since it seems plausible that control systems can be used to further improve the performance and profit of pipelay operations, as they have for several other industries, including the process industry, aerospace industry, and others [7].

Specifically, the paper is divided into two main sections, where the first section deals with pipelay fundamentals, while the second section deals with motion control issues. The paper also provides an extensive literature list to aid in further research on automated offshore pipelay operations. Experienced pipeline engineers will be familiar with parts of the presented material.

The main idea behind the concept of automatic control is to automatically force the value of a specific system output vari-

able to a desired value, as illustrated in Figure 1. This desired value is typically called a *setpoint* or a *reference*. The output of the system, which represents the interesting system behavior from an operational point of view, is a result of the internal system dynamics and our ability to manipulate the system through certain inputs. As already mentioned, the move toward an application of automatic control technology started when anchor systems were replaced by DP systems for the dynamic positioning of vessels involved in deepwater operations [8]. In the future, increasingly advanced control features can be introduced through the development of sophisticated guidance systems that reduce the need for manual DPO control to improve precision, speed and safety of the operation. By applying available pipe-monitoring sensors and commercial-off-the-shelf (COTS) DP systems, new functionality can be implemented without additional hardware costs.

## PIPELAY FUNDAMENTALS

This section deals mainly with identifying the inputs, states and outputs relevant for control in a pipelay operation, and starts with an introduction to the construction of offshore pipelines.

Over the preceding decades, development of offshore pipeline technology has mainly been reported at conferences such as the *Offshore Technology Conference* (OTC) [9], *International Conference on Offshore Mechanics and Arctic Engineering* (OMA) [10], and *Offshore Pipeline Technology* (OPT). However, during recent years, the field has become more accessible by the publication of several textbooks, which are partly complementary, partly overlapping. Non-technical approaches are taken in [11] and [12], while [2] and [13] provide useful introductions to technical aspects. A comprehensive overview of design methods aimed at both new and experienced pipeline engineers are provided in [14] and [15], while detailed mechanical design methods are found in [16].

## Pipeline Construction

*Pipelaying* encompass installation methods whereby the pipe string is welded together from pipe joints onboard a pipelay vessel as it is installed on the seabed [15]. Historically, for pipelay in shallow waters the pipe string was jointed horizontally on the open deck of the barge and extended down to the seabed in an S-shaped curve, commonly referred to as *S-lay*, see Figure 3. Tensioners grip the pipe string to facilitate construction during the pipelay, and are used to control the speed with which the pipe is extended from the vessel, called the *pay-out speed*. The upper part of the pipe string is supported by a submerged open frame structure, called a *stinger*, which controls its curvature. The main advantage with the S-lay method is that it enables a long *firing line* with parallel workstations for assembly of pipe joints, field coating and non-destructive testing, making the method fast and

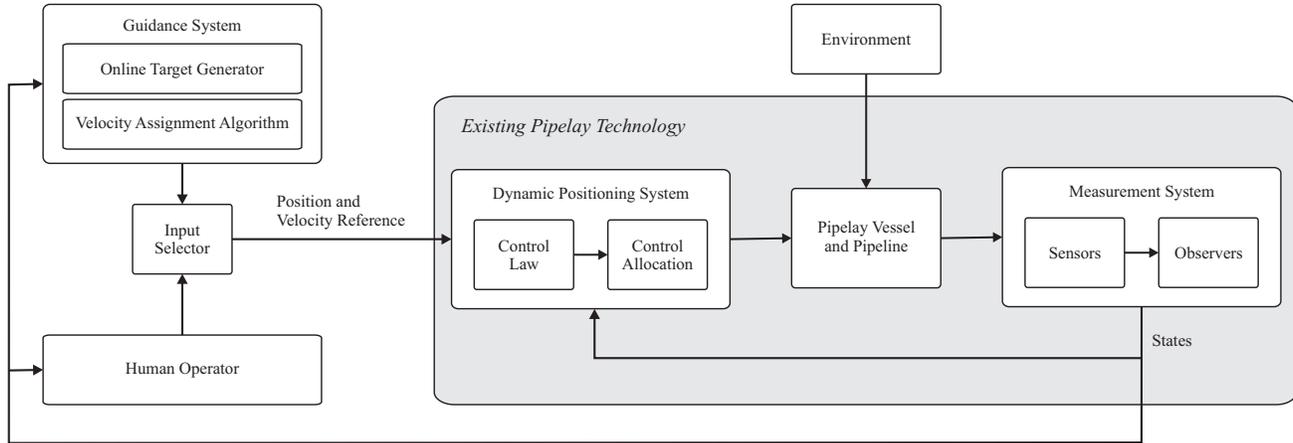


Figure 2. PIPELAY CONTROL SYSTEM ARCHITECTURE.

economical, particularly for long pipelines.

For large depths and pipe diameters, the pipe strains over the stinger may exceed the standard allowable strain levels, and the steel pipe may be deformed. To overcome this, the *J-lay* method was developed [17]. In the *J-lay* method, the pipe is extended on a near-vertical ramp, the *J-lay* tower, which eliminates the stinger and overbend strains altogether. Semi-submersibles are frequently used to facilitate *J-lay* due to their high stability, which is required for the tall *J-lay* tower. The main drawback with the method is that this tower only facilitates one workstation, making the *J-lay* method inherently slower than the *S-lay* method, which is the price paid for pipe installation at greater depths. These installation methods are thus complementary [18].

However, the *S-lay* method has recently been developed to also handle deepwater installation by the construction of very large dynamically positioned vessels with fixed stingers that support the pipe string down to a near-vertical lift-off point. This stinger configuration has shown to reduce the tension in the pipe compared to the traditional *S-lay* method. Furthermore, pipeline engineers argue that it will be safe to relax the standard strain level of the design in order to reach greater depths and handle even heavier pipelines [19].

*Reeling* is an installation method suitable for cables, umbilicals and flexible pipes which generally have small diameters. The method is also suitable for small-diameter rigid pipes (up to 16 inches). For reeling applications, the pipe is constructed on-shore in a controlled factory environment and spooled onto the reel. The pipe is then payed out by a reeling vessel with the reel mounted either horizontally or vertically. Since the pipe is deformed on the reel it must be mechanically straightened out during the installation, which takes either the *S-lay* or *J-lay* approach.

Depending on the installation method used, pipe properties, water depth and weather conditions, the length of pipe laid in a

day varies from 1-1.5 kilometers for *J-lay* and up to 5 kilometers for *S-lay*. A typical rate for reeling is 14 kilometers per day. More detailed overviews of installation methods can be found in [2, 13, 14, 15], and details on pipelay vessels and equipment can be found online at [20, 21, 22]. Note that so-called towing methods are not considered here.

The actual installation process is always overseen by an engineer, who operates the vessel together with the captain. The engineer relies on a team of three to four people, where each team member has a dedicated task of monitoring or operating equipment. A typical task breakdown may be:

1. Navigation (Surveyor)
2. Vessel maneuvering (DPO)
3. Tensioner/reeling/carousel operator
4. ROV operator.

The positioning of the vessel is done by a DP system, where reference positions are manually provided such that the vessel moves in a discrete fashion between consecutive references. The distance between these reference positions may vary in length, but the pipelay vessel will typically move in steps equal to the length of a pipe extension, which is limited by the length of the firing line. However, a reeling ship typically moves continuously since it can reel out its pipe continuously.

### Pipeline Installation

A pipeline development project is typically divided into three phases: *design*, *installation*, and *commissioning and operation*. In the design phase, the pipeline path and the pipe properties are determined. The path consists of straight and curved sections on the seabed which the pipe must be placed along, and is documented through detailed layout drawings, alignment sheets and bathymetry maps. The pipeline design phase also includes pipeline sizing (diameter and wall thickness) and material

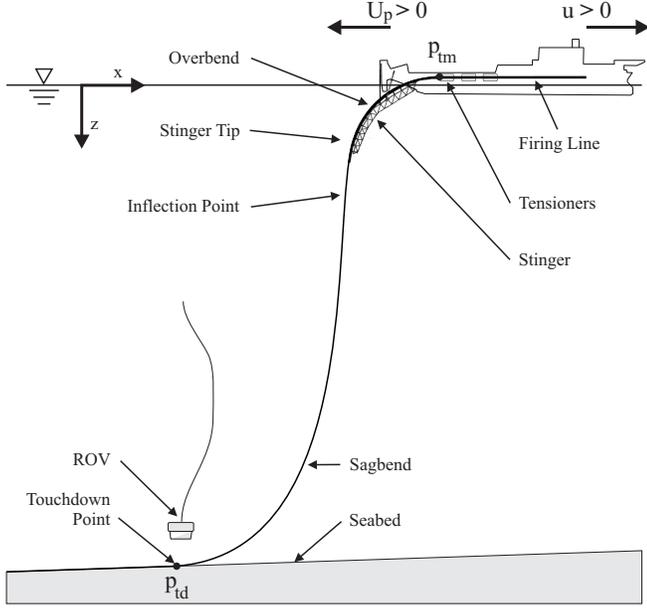


Figure 3. S-LAY PIPE CONSTRUCTION SCHEMATIC.

grade selection based on analyses of stress, hydrodynamic stability, span, thermal insulation, corrosion and stability coating, as well as riser specification. The choice of installation method can influence the design parameters of the pipeline.

In the literature, the term installation covers all the activities following the fabrication of the pipe joints until the pipeline is ready for commissioning and operation. However, in this paper, the term *installation* will be taken to mean the positioning of the pipe on the seabed only. From a control perspective, the S-lay and J-lay methods are similar, and the following definition of pipeline installation will be applied in the remainder of this paper:

**Definition 1. Pipeline Installation (Pipelay)** Pipeline installation is defined as the operation of positioning a pipeline on the seabed from a surface vessel. The pipe is extended from the vessel at a pay-out speed  $U_p(t) \geq 0$ , and at a departure angle  $\alpha \in [0, \pi/2)$ , defined relative to the mean sea surface.

For the S-lay method,  $\alpha = 0$ , and for J-lay,  $\alpha \approx \pi/2$ . For the on-site pipe-assembly methods, the pay-out speed  $U_p(t)$  will switch between  $U_p(t) = 0$  when the pipe is being constructed and  $U_p(t) > 0$  when the newly constructed pipe is payed out. Reeling allows a constant pay-out speed.

### Water Depth

Three regions of water depths are usually considered, referred to as *shallow*, *deep* and *ultra-deep* waters. The numerical values covered by each region are constantly increased as pipelay operations move to increasingly deeper waters. A better method

of classification might instead be to consider the significant loads on the pipe in each region.

In *shallow water*, the bending stiffness is significant, and static computational results on bending and stress loads are good approximations of the true loads. For S-lay, the departure angle at the lift-off point will be in the vicinity of  $30^\circ$  from the horizontal for a water depth of 100 m. Relatively small vessel movements have large impacts on the pipe configuration and stresses for such depths.

In *deep water*, the effect of the bending stiffness becomes insignificant with respect to the axial loads and dynamic effects such as vortex induced vibrations (VIV), and the dynamic behavior of the pipe must also be considered.

In *ultra-deep waters*, pipes are made very solid to withstand the external pressure at the seabed. These heavy and long pipes cause an extreme vertical tension for the tensioners to handle. For S-lay, the departure angle becomes close to vertical in order to keep the tension within reasonable limits, also known as *Steep S-lay*.

### Pipelay System and States

The total pipelay system to be controlled consists of the combination of the pipelay vessel and the pipeline, suspended freely in the water down to the touchdown point at the seabed. Following [23], the vessel is considered to be a *rigid body*, whose kinetics can be represented in 6 degrees of freedom (DOFs) as

$$\mathbf{M}\dot{\boldsymbol{\nu}} + \mathbf{C}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{D}(\boldsymbol{\nu})\boldsymbol{\nu} + \mathbf{g}(\boldsymbol{\eta}) = \boldsymbol{\tau}, \quad (1)$$

where the state vectors of generalized position and velocity are

$$\boldsymbol{\eta} = [x, y, z, \phi, \theta, \psi]^T \in \mathbb{R}^3 \times \mathbb{S}^3, \quad (2)$$

$$\boldsymbol{\nu} = [u, v, w, p, q, r]^T \in \mathbb{R}^6. \quad (3)$$

The matrices  $\mathbf{M}$ ,  $\mathbf{C}$  and  $\mathbf{D}$  represent inertia, Coriolis and damping effects respectively,  $\mathbf{g}$  is a vector of restoring forces and moments, while  $\boldsymbol{\tau}$  represents control inputs, environmental disturbances, and pipeline effects. The model (1) is a convenient representation which captures the main vessel-ocean-pipe effects, and has been adopted as a standard for vessel control design and analysis purposes.

The pipe is considered to be an *elastic body*, which is described by its *configuration*. The pipe configuration is the complete specification of the location and orientation of every point of the pipe. Let the *line of centroids* of the pipe be represented by the smooth curve  $\varphi : [0, L] \rightarrow \mathbb{R}^3$ , where  $L$  is the total length of the undeformed pipe, and a centroid is the geometric center of a cross-section of the pipe. For the material variable  $S \in [0, L]$ , the position of any point on the line of centroid is given by  $\varphi(S)$

and the orientation of the cross-section at  $\varphi(S)$  relative to an inertial frame is given by the rotation matrix  $\mathbf{R}(S)$ . The set of all configurations is then called the *configuration space*, which is given by

$$\mathcal{C} \triangleq \{(\varphi, \mathbf{R}) \mid S \in [0, L] \rightarrow \mathbb{R}^3 \times \text{SO}(3)\}. \quad (4)$$

Let  $\hat{\mathcal{C}} \subset \mathcal{C}$  be the set of all pipe configurations for which the pipe structural integrity is guaranteed. It is then required that the configuration stays in  $\hat{\mathcal{C}}$  at all times during the pipelay operation.

While the geometry of the line of centroids is given by  $\varphi$ ,  $\mathbf{R}$  is required to represent pipe extension, shearing, bending and twist, which is used to derive stress and strain in the pipe. For implementation in a computer, the continuous model must be discretized, e.g., by the finite element method. Details on mathematical pipe models are beyond the scope of this paper, and the reader is encouraged to consult [24] and the references therein.

The common standards used for pipeline design employ a design practice based on so-called *limit states* [25]. All relevant failure modes for a pipe are formulated as limit states, which can be organized on a vectorial form by  $\lambda$ . The safe region for the values of the limit states  $\hat{\lambda}$  is conservatively computed in the design phase. If the limit state values stay within their safe region during installation, the configuration is guaranteed to stay within  $\hat{\mathcal{C}}$ ,

$$\lambda_i \leq \hat{\lambda}_i \quad \forall i \in [1 \dots n] \quad \rightarrow \quad (\varphi, \mathbf{R}) \in \hat{\mathcal{C}}. \quad (5)$$

where  $n$  is the number of limit states. Following the DNV OS-F101 [25], limit states are classified into one of the four categories:

1. Serviceability Limit State (SLS)
2. Ultimate Limit State (ULS)
3. Fatigue Limit State (FLS)
4. Accidental Limit State (ALS),

where the limit state values are derived through simplified design formulas. These formulas use pipe properties and pipelay parameters as their input. Details on the limit states are beyond the scope of this paper. Other standards and recommended practices are found in API RP 1111 [26], ISO 13623 [27] and BS 8010 [28].

If the vessel DP system cannot keep the configuration in  $\hat{\mathcal{C}}$  due to environmental or other conditions, the pipe may buckle or collapse. To avoid this from happening, the pipe is lowered to the seabed in an abandonment procedure for protection. When the conditions have improved, the pipe is retrieved and the operation continued.

## Pipeline Configuration

The configuration of the pipe is determined by the *pipe properties*, the *pipelay parameters* and the *installation method*. The pipe properties refer to structural properties of the pipe such as the pipe diameter, submerged unit weight, bending stiffness (EI) and axial stiffness (EA). These properties are determined in the design phase and cannot be changed during the installation operation. The pipelay parameters refer to the conditions under which the pipelay takes place, and the most important parameters include:

1. Boundary conditions
2. Axial lay-tension
3. Pipe departure angle from the stinger
4. Water depth
5. Stinger curvature radius
6. Stinger roller positions
7. Environmental loads.

The pipe extends beyond the freely suspended configuration on both sides, represented by the touchdown point  $\mathbf{p}_{td}$  and the position of the last tension machine along the firing line  $\mathbf{p}_{tm}$ , see Figure 3. The lower boundary condition is given by the position and orientation at the touchdown point, while the upper boundary condition is given by the position and orientation of the pipelay vessel. The lay-tension  $T$  is governed by the difference in  $\mathbf{p}_{td}$  and  $\mathbf{p}_{tm}$ , and the length of the pipe in between. For the static planar case, this situation can be well represented by the catenary equation. Also, since pipelaying is a low-speed application, catenary considerations may give good lay-tension approximations.

The stinger curvature radius and the positioning of the rollers are determined in the design phase and remains fixed during the operation. The environmental loads are represented by 1<sup>st</sup> and 2<sup>nd</sup> order waves loads as well as current loads, but wave excitation forces only affect the pipe near the surface, typically down to 20 meters depth. Different current profiles will give different configurations. For more on sea loads, see [29].

Geometrically, three distinct sections of the configuration must be considered [30, 31, 19], namely the *sagbend*, the *overbend*, and the *stinger tip*.

*The sagbend* is defined as the pipe section that extends from the touchdown point to the stinger tip or inflection point. In the sagbend, the static load effect is governed by the tension, pipe submerged weight, external pressure and bending stiffness. The equilibrium configuration is load-controlled since there are no physical boundaries for the deformations that the pipeline can experience, so that the configuration in the sagbend is essentially the same for every deepwater installation method. This shape is known as the *catenary* and is well known in the literature [32].

*The overbend* is defined as the pipe section from the tension equipment over the stinger and to the stinger tip or inflection point. The stinger supports the pipe on rollers spaced out

along its length. The roller contacts are monolateral and can be considered a boundary condition to the achievable possible configuration of the pipeline. From the third roller counted from the tip and up, the pipe is *displacement-controlled* [30]. Note that the local loads on the stinger do not propagate beyond the inflection point, and also that the J-lay method does not have an overbend region.

*The stinger tip or intermediate region* is defined as the pipe section that extends from the third-last stinger roller and down to the inflection point. For the stinger tip, the main concern is the dynamic load effect caused by the contact of the pipe with the last roller, which can cause very high and uncontrolled dynamic bending loads. Consequently, the pipe liftoff from the stinger is usually required to occur before the last roller.

### Available Measurements

The condition of the pipe is closely monitored during the pipelay by a measurement system that provides state measurements from filtering of sensor data and from state estimators. The instrumentation varies with different vessels based on size, operational depth and installation method, and the following measurements are considered here:

1. Vessel position and velocity
2. Touchdown position
3. Axial tension
4. Departure angle
5. Roller pressure
6. Free-span pipe length
7. Touchdown distance
8. Water depth
9. Environmental loads (current, wind, waves).

*Vessel position and velocity* - The vessel position may be obtained with high accuracy from a number of available position reference systems, including the global positioning system (GPS), hydroacoustic position reference (HPR) and microwave position reference systems [8]. Since pipelaying is done over long distances, using GPS with corrections (DGPS) is very common and provides an accuracy of up to 0.1 meters. GPS also provides vessel velocity measurements.

*Touchdown position* - A remotely operated vehicle (ROV) is used to hover over the touchdown point and provide a visual image. It is not easy to define the exact touchdown point since the seabed is uneven and penetrable, so the position of the touchdown point  $\mathbf{p}_{td}$  is commonly assumed to coincide with the ROV position. Multiple ROVs may also be used to monitor other parts of the pipe in the water.

*Axial tension* - The purpose of applying tension to the pipeline through tension machines is to control the curvature of the sagbend and the moment at the stinger tip through supporting the submerged weight of the suspended part of the pipe. The

tension exerted on the tensioners from the pipe depends on the pipe properties and configuration.

*Departure angle* - The departure angle of the pipe leaving the stinger is estimated from the contact force on the rollers and/or closed-circuit television (CCTV) equipment on the stinger. An equivalent term is *lift-off angle*.

*Roller pressure* - Rollers are spaced out along the stinger, supporting the overbend and reducing the strain. The rollers are equipped with pressure cells to measure the contact force from the pipe. These measurements are used to ensure that the pipe follows the stinger smoothly, and good practice indicates that the pipe should lift off from the stinger before the last roller. CCTV equipment may also be used for this purpose.

*Free-span pipe length* - Since each link joint is numbered sequentially, visual identification of the joints at the touchdown point and at the vessel means that the length of the suspended pipe  $L$  can be found.

*Touchdown distance* - The horizontal distance between  $\mathbf{p}_{tm}$  and  $\mathbf{p}_{td}$ , also known as the *lay-back* distance.

*Water depth* - Measurements of the water depth are readily acquired from acoustic sensors located on the pipelay vessel. At the touchdown point, the ROV will measure its depth using pressure sensors.

*Environmental loads* - The wind will influence the vessel position, but the direction and speed of the wind is easily measured and compensated for by the DP system. Currents and second-order wave loads can also be accounted for by the DP system, but loads on the pipe cannot be avoided. Nor can first-order wave effects, which make the vessel roll, pitch and heave.

### Actuators for Tension Control

Several aspects are considered when a desired pipe tension is determined. The axial tension in the pipe has a vertical and a horizontal component. The vertical component is dictated by the water depth and the unit weight, and is passively compensated for by the pipelay vessel restoring forces. The horizontal tension is left to active control by the motion control system, and to find the optimal tension, several economical and practical factors must be considered.

There are several reasons to keep low horizontal tension at the touchdown point. Low tension will reduce free spans and also allows for shorter radii of the curved segments, which will reduce the need for seabed preparations. The ROV used for monitoring the touchdown point has a limited range, and low horizontal tension will move the touchdown point closer to the pipelay vessel so that the ROV can be operated from this vessel. Reduced tension also reduces the fuel consumption of the surface vessel. The residual tension, which is the tension left in the pipe after installation, is also reduced with reduced lay tension, and should be as small as possible. However, too little tension will cause the pipe to buckle. A graph of tension vs. cost is shown in Figure 4.

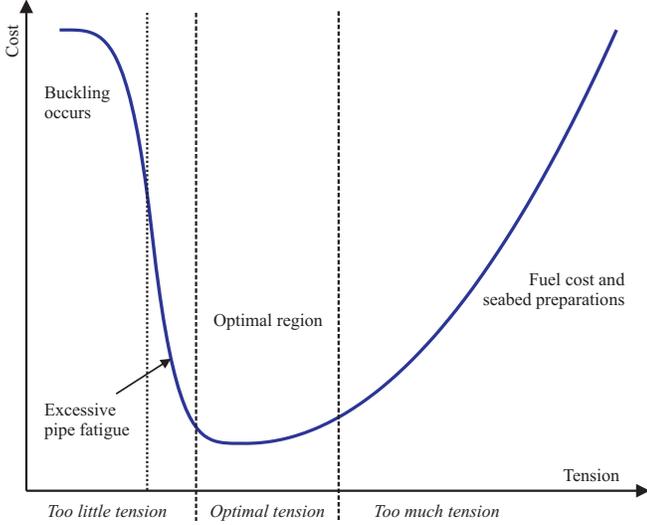


Figure 4. TENSION VS. COST.

The horizontal tension  $T_h$  acting on the pipe can be considered as a nonlinear spring where the displacement is given by the touchdown distance, and the spring coefficient  $k$  is a function of the touchdown distance and other pipe properties and parameters, such that

$$T_h = k \|\mathbf{p}_{tm} - \mathbf{p}_{td}\|. \quad (6)$$

A quasi-static method based on the natural catenary equation [32] is commonly used to compute this tension. The change in tension is then proportional to  $u - U_p$ , when the x-axis of the vessel-fixed BODY frame is aligned with the line of tensioners. The actuators (control inputs) for controlling  $T_h$  are thus the position and velocity of the vessel, as well as the speed at which the pipe is extended from the vessel, i.e., the pay-out speed. In addition, the stinger configuration can be used to modify the tension if it can be dynamically controlled. Consequently, the actuators discussed in the following are:

1. Vessel position and velocity
2. Pay-out speed
3. Stinger configuration.

*Vessel position and velocity* - These variables have a direct impact on the pipe tension and thus the position of the touchdown point  $\mathbf{p}_{td}$ . Dynamically positioned pipelay vessels keep their position exclusively by active use of thrusters, and fully actuated vessels are required for precision positioning in surge, sway and yaw. Background on DP systems is found in [8], [23] and [33], while a DP system reference manual can give a hands-on introduction [6]. The pipelay vessel must also keep a specific heading, and is not at liberty to freely weathervane in order to reduce the

impact of the environmental loads. Tug-boat support may occasionally be used to keep position if the thruster capacity becomes insufficient.

*Pay-out speed* - The tensioners hold on to the pipe with rolling tracks that allow pipe pay out while maintaining tension on the pipe. The pay-out speed  $U_p$  is considered positive when the pipe is payed out, and its maximum value is limited by the mechanical properties of the tensioners.

*Stinger configuration* - The stinger configuration can be operated by hydraulics or cranes, but once the stinger configuration has been fixed it cannot be changed easily. However, for cables and light pipes, it seems possible to alter the stinger configuration during operation by using hydraulics or cranes. Still, this method is currently not in use, and it is therefore not reasonable to consider the stinger configuration as an active actuator, but rather as a rigid support structure for the pipe, designed in advance. The stinger of the Allseas vessel Solitaire is described in [34] and [35].

## MOTION CONTROL ISSUES

A vehicle motion control system can be conceptualized to involve at least three levels of control in a hierarchical structure as illustrated in Figure 5 [36]. The highest control level, termed the *guidance level*, is responsible for prescribing vessel guidance commands to solve the pipelay problem. The intermediate level then encompass COTS DP controllers, which give commands through a control allocation algorithm to the low-level actuator controllers that manipulate the actual vessel propellers and thrusters.

An objective of this paper is to motivate the design of guidance systems that can replace the human operator at the highest control level. Such guidance systems can conceptually be divided into an *online target generator* and a *velocity assignment algorithm*, see Figure 2. While the target generator computes the virtual target point on the sea surface which the pipelay vessel must track for the touchdown point to follow the seabed reference path, the velocity assignment algorithm computes the associated reference velocity. Both reference position and velocity are subsequently fed to a COTS DP system.

At least two distinct approaches can be taken in the guidance system design:

1. In a *protocol-based* approach, the system tries to imitate a human operator based on a set of rules obtained from quantifying the operational procedure which the operator follows. The system is then implemented as a flow diagram, which is simple to implement, but which at best will perform the task only as well as the human operator.
2. In a *model-based* approach, the system computes the guidance signals based on mathematical models of the pipelay system. The great advantage of a computer-based controller

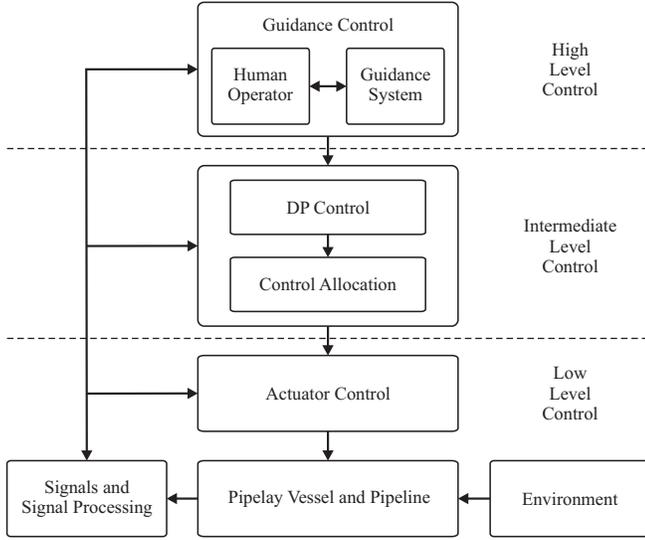


Figure 5. MOTION CONTROL HIERARCHY.

is the available computational power, which allows for computation of decision data based on real-time measurements, thus yielding more accurate results than data based on test scenarios. The performance of a model-based guidance system can thus potentially exceed that of a human operator. Advanced pipeline models are available, such as the nonlinear dynamic finite strain model presented in [37]. However, simpler models such as the robot-equation-based model presented in [38] are better suited for model-based feedback control in real-time. In the accompanying paper [24], mathematical models used for pipelay design and simulation are considered for control applications.

Note that in this scenario the human operator is still a part of the system, but now only left to monitor the operation.

### The Pipelay Problem

The overall objective of a pipelay operation is to position a pipeline along a desired seabed path from a start point to an end point while simultaneously ensuring pipeline integrity. All motion controllers try to achieve a control objective, and for pipeline installation the main control objective can be stated as:

**Definition 2. The Pipelay Problem** *The pipelay problem is defined as the task of laying a pipeline along a pre-specified reference path on the seabed through active motion control of a pipelay vessel. The structural integrity of the pipe must be guaranteed at all times during the operation.*

The primary objective of the pipelay problem is thus to position the touchdown point as close as possible to the reference path on the seabed. A secondary objective can then be to move the touchdown point at a desired speed along this path. Thus, the

touchdown point faces a so-called *path-maneuvering problem*, see [36] and [39]. These two objectives must be satisfied such that the structural integrity of the pipe is ensured. Hence, the surface vessel must move such that both the path-maneuvering objective of  $\mathbf{p}_{td}$  and the pipe structural integrity is satisfied simultaneously. The pipelay vessel DP system must then track an instantaneously computed reference value for  $\mathbf{p}_{tm}$  to achieve both objectives, and thus satisfy a *target-tracking* motion control objective [36]. This objective corresponds to motion control scenarios where the target motion is not known a priori, which is the case for our application since the target is dynamically computed based on  $\mathbf{p}_{td}$ ,  $\mathbf{p}_{tm}$ ,  $U_p$ , environmental conditions, and a desired tension. Hence, the surface vessel must achieve target tracking for  $\mathbf{p}_{tm}$  such that  $\mathbf{p}_{td}$  satisfies its path-maneuvering objective. An analogous application can be found in [40], where a DP-controlled semi-submersible must chase a virtual setpoint on the sea surface to minimize bending stresses on a riser extending from the vessel to a stationary installation on the seabed. The pipelay problem can thus be seen as a dynamic version of this setpoint chasing application.

Note that the pipelay problem definition is independent of pipe diameter, water depth, installation method, departure angle, and whether an automatic controller is used or not.

### Subsea Path

Let the subsea path  $\mathcal{P}$  consist of a finite set of  $n$  straight-line segments connecting  $n - 1$  waypoints, each with an associated turn radius  $r_i$ ,  $i \in \{1, \dots, n\}$ , organized in a waypoint table. The location of each waypoint is given by the position vector  $\mathbf{p}_i \in \mathbb{R}^3$ , stated relative to an inertial Earth-fixed reference frame. The turn radii ensure a smooth transition between consecutive line segments, and the path  $\mathcal{P}$  is thus implicitly parameterized as a set of connected straight and curved segments, see Figure 6. Only one segment is in active use at a time.

Let  $\mathcal{D}$  then define the part of the seabed which is located within a distance  $\delta > 0$  of  $\mathcal{P}$ , coinciding with the breadth of the seabed preparations, done, e.g., by trenching, dredging, or rock dumping. Depending on the seabed conditions, this corridor has a typical width of 1-10 meters.

During pipelay, the goal is to have  $\mathbf{p}_{td} \in \mathcal{D}$ , and for  $\mathbf{p}_{td} \notin \mathcal{D}$ , a fault condition has occurred which must be corrected. A switching between the nominal and some fault-recovery controllers must then be performed to ensure that the situation is properly handled such that the pipe can be placed within  $\mathcal{D}$  again. The field of *fault-tolerant control* deals with such scenarios [41].

### Vessel Path

Representing the vessel position by  $\mathbf{p}_{tm}$ , a nominal vessel path  $\mathcal{V}$  can be found by purely kinematic considerations, which is valid under the following assumptions: Dynamic effects can

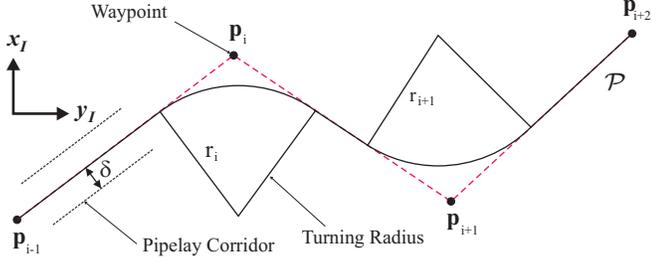


Figure 6. SUBSEA PATH PARAMETERIZATION.

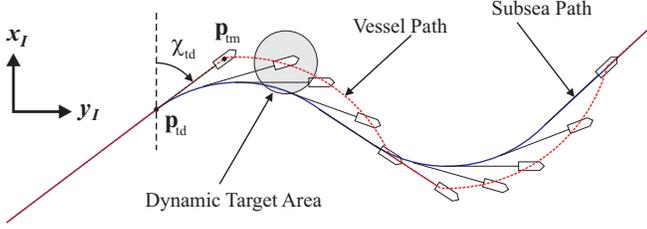


Figure 7. SUBSEA PATH AND CORRESPONDING VESSEL PATH.

be neglected due to low speeds, no environmental loads, and the water depth is constant for each segment, see Figure 7.

Let the position of a point on  $\mathcal{P}$  be represented by  $\mathbf{p}_{td}(\varpi) \in \mathbb{R}^2$ , where  $\varpi \in \mathbb{R}$  is a scalar variable. For straight-line segments (zero curvature), the desired vessel position can then be computed by

$$\mathbf{p}_{tm}(\varpi) = \mathbf{p}_{td}(\varpi) + \mathbf{R}(\alpha_i) \begin{bmatrix} \|\mathbf{p}_{tm} - \mathbf{p}_{td}\|_d \\ 0 \end{bmatrix}, \quad (7)$$

where

$$\mathbf{R}(\alpha_i) = \begin{bmatrix} \cos \alpha_i & -\sin \alpha_i \\ \sin \alpha_i & \cos \alpha_i \end{bmatrix} \quad (8)$$

and

$$\mathbf{p}_{td}(\varpi) = \begin{bmatrix} x_i + \varpi \cos \alpha_i \\ y_i + \varpi \sin \alpha_i \end{bmatrix}, \quad (9)$$

where  $\alpha_i$  is the orientation of the straight-line subsea path and  $\|\mathbf{p}_{tm} - \mathbf{p}_{td}\|_d$  is the desired touchdown distance corresponding to a desired pipeline tension. For subsea segments with varying curvature, the vessel position can be computed by

$$\mathbf{p}_{tm}(\varpi) = \mathbf{p}_{td}(\varpi) + \mathbf{R}(\chi_{td}(\varpi)) \begin{bmatrix} \|\mathbf{p}_{tm} - \mathbf{p}_{td}\|_d \\ 0 \end{bmatrix}, \quad (10)$$

where  $\mathbf{p}_{td}(\varpi)$  now depends on the particular path and  $\chi_{td}(\varpi)$  is the tangential direction of the curved subsea path at  $\varpi$ , see Figure 7.

### Vessel Target

Unfortunately, the kinematically computed vessel paths associated with (7) and (10) do not suffice in a practical pipelay operation. They only provide approximations that are valid for ideal operating conditions, including nice weather and minimum current. In practice, the vessel must track a dynamic target located at a distance from the ideal location in order for  $\mathbf{p}_{td}$  to be within  $\mathcal{D}$  while simultaneously ensuring pipeline structural integrity, see Figure 7. Today, this target is manually computed by a DPO based on previous experience through various offset parameters available in the DP system. A future goal is thus to compute this target dynamically by using mathematical models and real-time measurements to be able to achieve an even greater degree of accuracy and effectiveness in the pipelay operation.

### CONCLUSIONS

This paper has considered offshore pipelay operations from a control perspective. Specifically, the first part of the paper has given a thorough introduction to the fundamentals of pipelay operations and the challenges and possibilities associated with such operations. The second part then suggested how pipelay operations can be further automated by augmenting the manually-operated dynamic positioning (DP) systems of today with sophisticated guidance functionality that may improve operational precision and safety, as well as enabling pipelay vessels to take on the challenges of installing pipelines in even deeper waters and more hostile environments, by relying on advanced mathematical models.

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### REFERENCES

- [1] Collier, G. P., and Rosier, P., 1995. "Environmental impact of submarine pipeline installation". *Journal of Offshore Technology*, **3**(2), pp. 9–14.
- [2] Palmer, A. C., and King, R. A., 2008. *Subsea Pipeline Engineering*, 2nd ed. PennWell Books.
- [3] Anonymous, 1987. "From car ferry to pipelaying vessel". *Diesel & Gas Turbine Worldwide*, **19**(1), pp. 52–54.

- [4] Anonymous, 1987. "New electrical concept for DP thruster control". *Ocean Industry*, **22**(2), p. 177.
- [5] Heerema, E. P., 1998. "Major deepwater pipelay vessel starts work in North Sea". *Oil and Gas Journal*, **96**(18), pp. 78–82.
- [6] KONGSBERG MARITIME AS, 2006. *Kongsberg K-Pos DP Dynamic Positioning System*. Report no. 301093/B.
- [7] Åström, K. J., 1996. *Automatic control: A perspective*. Colloquium on Automatic Control, Vol. 215 of Lecture Notes in Control and Information Sciences. Springer Berlin / Heidelberg, pp. 1–26.
- [8] Bray, D., 2003. *Dynamic Positioning*, 2nd ed., Vol. 9 of *Oilfield Seamanship*. Oilfield Publications Limited.
- [9] Offshore Technology Conference. <http://www.otcnet.org>.
- [10] OMAE. <http://www.omaе.org>.
- [11] Leffer, W. L., Pattarozzi, R., and Sterling, G., 2003. *Deep-water Petroleum Exploration & Production: A Nontechnical Guide*. PennWell Books.
- [12] Miesner, T. O., and Leffler, W. L., 2006. *Oil & Gas Pipelines in Nontechnical Language*. PennWell Books.
- [13] Guo, B., Song, S., Chacko, J., and Ghalambor, A., 2005. *Offshore Pipelines*. Gulf Professional Publishing.
- [14] Bai, Y., and Bai, Q., 2005. *Subsea Pipelines and Risers*. Elsevier.
- [15] Braestrup, M. W., Andersen, J. B., Andersen, L. W., Bryndum, M. B., Christensen, C. J., and Rishy, N., 2005. *Design and Installation of Marine Pipelines*. Blackwell Science Ltd.
- [16] Kyriakides, S., and Corona, E., 2007. *Mechanics of Offshore Pipelines, Volume 1: Buckling and Collapse*, 1 ed. Elsevier.
- [17] Wilkins, J. R., 1994. "From S-lay to J-lay". In Proceedings of the 13th Int. Conference on Offshore Mechanics and Arctic Engineering, New York, NY, USA.
- [18] Perinet, D., and Frazer, I., 2007. "J-lay and Steep S-lay: Complementary tools for ultradeep water". In Proceedings of the 39th Offshore Technology Conference. OTC 18669.
- [19] Perinet, D., and Frazer, I., 2008. "Strain criteria for deep water pipe laying operations". In Proceedings of the 40th Offshore Technology Conference. OTC 19329.
- [20] The Acergy Group. <http://www.acergy-group.com>.
- [21] Allseas. <http://www.allseas.com>.
- [22] Subsea7. <http://www.subsea7.com>.
- [23] Fossen, T. I., 2002. *Marine Control Systems: Guidance, Navigation, and Control of Ships, Rigs and Underwater Vehicles*, 1st ed. Marine Cybernetics, Trondheim Norway.
- [24] Jensen, G. A., and Fossen, T. I., 2009. "Mathematical models for model-based control in offshore pipelay operations". In Proceedings of the 28th OMAE, Honolulu, Hawaii, USA.
- [25] DNV, 2000. *Offshore Standard DNV-OS-F101 Submarine Pipeline Systems*.
- [26] API, 1998. *API RP 1111*. Design, Construction, Operation, and Maintenance of Offshore Hydrocarbon Pipelines.
- [27] ISO, 2000. *ISO 13623:2000 – Petroleum and natural gas industries – Pipeline transportation systems*.
- [28] BSI, 1993. *BS 8010*. Code of Practice for Pipeline - Part 3. Pipeline Subsea: Design, Construction and Installation.
- [29] Faltinsen, O. M., 1990. *Sea Loads on Ships and Offshore Structures*. Cambridge University Press.
- [30] Callegari, M., Canella, F., Titti, F. M., Bruschi, R., Torselletti, E., and Vitali, L., 2000. "Concurrent design of an active automated system for the control of stinger/pipe reaction forces of a marine pipelaying system". In Proceedings of the Int. Workshop on Harbour, Maritime & Multimodal Logistics Modelling and Simulation, Portofino, Italy.
- [31] Torselletti, E., Bruschi, R., Vitali, L., and Marchesani, F., 1999. "Lay challenges in deep waters: Technologies and criteria". In Proceedings of the 2nd Int. Deepwater Pipeline Technology Conf., New Orleans, Louisiana, USA.
- [32] Irvine, H. M., 1981. *Cable Structures*. The MIT Press.
- [33] Fay, H., 1990. *Dynamic Positioning Systems: Principles, Design and Applications*. Éditions Technip.
- [34] Heerema, E., 2005. "Recent achievements and present trends in deepwater pipe-lay systems". In Proceedings of the 37th Offshore Technology Conference. OTC 17627.
- [35] Steenhuis, A. L. J., van Norden, T., Regelink, J., and Krutzen, M., 2007. "Modifications to the pipelay vessel Solitaire for the Independence trail project". In Proceedings of the 39th Offshore Technology Conference. OTC 19059.
- [36] Breivik, M., and Fossen, T. I., 2008. "Guidance laws for planar motion control". In Proceedings of the 47th IEEE Conference on Decision and Control, Cancun, Mexico.
- [37] Jensen, G. A., 2009. "Modeling and control of offshore pipelay operations". PhD thesis, Norwegian University of Science and Technology.
- [38] Jensen, G. A., Transeth, A. A., Nguyen, T. D., and Fossen, T. I., 2008. "Modelling and control of offshore marine pipeline during pipelay". In Proceedings of the 17th IFAC World Congress, Seoul, Korea.
- [39] Skjetne, R., Fossen, T. I., and Kokotović, P. V., 2004. "Robust output maneuvering for a class of nonlinear systems". *Automatica*, **40**(3), pp. 373–383.
- [40] Sørensen, A. J., Leira, B., Strand, J. P., and Larsen, C. M., 2001. "Optimal setpoint chasing in dynamic positioning of deep-water drilling and intervention vessels". *International Journal of Robust and Nonlinear Control*, **11**(13), pp. 1187–1205.
- [41] Blanke, M., Kinnaert, M., Lunze, J., and Staroswiecki, M., 2006. *Diagnosis and Fault-Tolerant Control*, 2nd ed. Springer.