DIGITAL OFFSHORE ACOUSTIC PIG TRACKING WITH MULTIPATH ROBUSTNESS

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Acoustic Pig Tracking

Acoustic pipeline pig tracking, simply put, is the attachment of a battery powered acoustic pinger to a pipeline pig; the acoustic signal generated by the pinger travels through the pipeline and into the surrounding water and is subsequently tracked with a suitable receiver system.

Receivers consist of a hydrophone, essentially an aquatic microphone tuned to the frequencies of interest, and some sort of user interface which displays, or more often plays back downshifted audio of the ping.

The hydrophones attached to receivers can be either omni-directional or directional depending on the task at hand. For tracking from a surface vessel, omni-directional is often the obvious choice. However, when precise locating of the pinger is required, a directional hydrophone can be used.

The energy emitted by the acoustic pinger are acoustic tones, often only a few milliseconds long and outside the range of human hearing, typically between 10kHz and 40kHz.

Acoustic pig tracking itself is not a new field. For decades pinger suppliers have supplied pinger equipment to offshore pipeline construction companies and pipeline operators alike. These pingers, when properly mounted on pipeline pigs, have provided these basic offshore pig tracking functions.

The conditions for the use of acoustic pingers to track pipeline pigs are somewhat narrow:

1. The pipeline must be offshore and surrounded by water
2. The medium inside the pipeline must be a liquid
3. The pipeline must have little or no burial beneath the sea bed
4. The pipeline typically cannot be a pipe-in-pipe or other complex assembly

However, the benefits of acoustic tracking are strong:

1. The range of acoustic pingers can be several kilometers
2. Basic “leapfrog” tracking is possible from shipside
3. Locating a stuck pig within a few meters is possible with directional hydrophones and a diver or ROV
4. Different frequencies allow unique identification of pigs in a train

Despite this list of strong positive features, acoustic pig tracking has a somewhat spotty record of reliability in the field. Over the years CDI has had the opportunity to speak with many of the end-users of acoustic equipment. Anecdotal end user experiences have varied widely, with some firms having good experiences and others having complete failures.

Some of the failures of the systems are no doubt due to a lack of understanding and training of the operator; user error. This is not uncommon when infrequently used systems are put into the hands of end users. However, user error cannot account for all of the failures experienced by otherwise competent operators. There are some subtle underlying technical problems with existing acoustic pig tracking systems.

Perhaps greatest among these is multipathing.

Acoustic Multipathing

If the “ping” of acoustic pingers is likened to “ringing a bell”, multipathing are its echoes. In Figure 1 we see a number of acoustic reflectivity sources. Solid obstacles, such as offshore platforms or other sea-bottom structures, as well as thermoclines, the layers of water differing in temperature, and even the surface and bottom of the ocean all reflect a pinger’s energy.

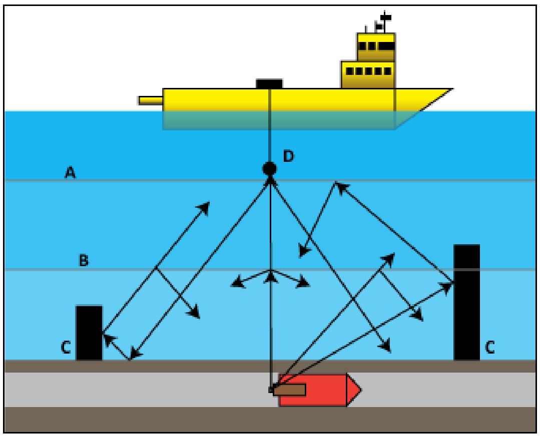

Figure 1 - Multipathing Reflectivity

As the pinger's radiated energy reaches the hydrophone from these various reflected sources, the phase differences of the reflected waveforms have additive and subtractive effects. This results in a signal which grows stronger or weaker depending solely upon the relative positions of the pinger and hydrophone in their environment. It is entirely possible to be quite near a pinger source and simply not be able to detect it, or to have its signal strength rise and fall noticeably based on the superposition of the signal from different paths. Moreover, the effect of multipathing cannot be mitigated by signal strength.

Even when conditions are good, existing systems convey precious little information. Multiple frequencies of pingers may be attached to different assets in order to differentiate them, and one system can alter the frequency it emits in response to external stimuli such as a wire break on a gauging plate.

These are useful techniques, however, acoustic technology outside of the pig tracking market has made many advances in recent years. Many of us are familiar with acoustic digital modems and telemetry systems capable of sending data through the water – why not bring these techniques into the area of pig tracking and locating?

SeaTrack

Over a year ago now, CDI, which specializes in pipeline pig location and tracking systems, embarked upon a research and development project which was dubbed “SeaTrack”. This development project set about to identify and to overcome the problems associated with existing acoustic pipeline pig tracking systems which reduce their reliability and ultimately their usefulness and cost effectiveness.

CDI set ambitious goals:

1. To develop a commercially viable system which was equally useful for pig tracking and generic offshore asset tracking and locating.

2. To have the ability to send digital information from the pinger to the receiver either in response to sensors embedded within the pinger or signals sent to the pinger from the tracked asset.

3. To be able to provide the speed of the asset to an operator in knots or kilometers per hour.

4. To be able to provide the operator with target position and velocity relative to the receiver; the actual estimated location of the pig and not simply the knowledge that the operator was within the sphere of detection of the pinger.

5. Ultimately, the creation of an acoustic pig and asset tracking system which would allow for the continuous and near real-time tracking of a moving target from a moving vessel without the need to incur the risk and cost of a diver or ROV.

CDI's SeaTrack project has met those goals.

Working with global acoustic transmission experts, CDI has developed a signaling method which utilizes a complex multi-frequency ping technique, which are referred to as “chords”, one of which is shown in Figure 2. This image illustrates the separate frequencies contained within a single ping from a SeaTrack pinger.

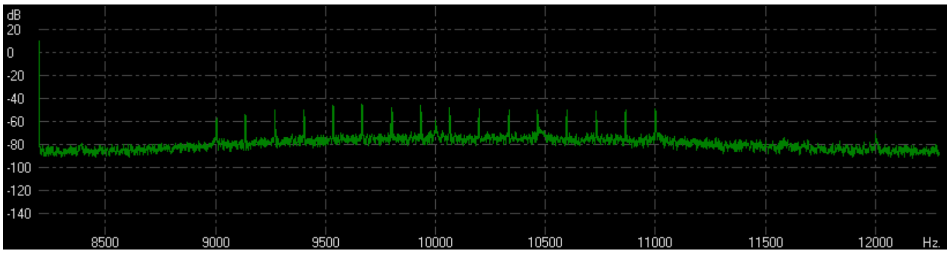

Figure 2 - SeaTrack Chordal Ping

These chordal pings are transmitted by a Free Flooding Ring projector shown in Figure 3 which provides high efficiency at its resonant frequencies and relatively compact size at low frequencies. FFRs also radiate the majority of their energy broadside with very little energy transmitted axially. This works well for pig-mounted applications where energy projected down the pipeline is mostly lost.

Figure 3 - SeaTrack's Free Flooding Ring (FFR) transducer

A SeaTrack ping utilizes a chord of 15 separate frequencies, transmitted simultaneously between 9 and 11kHz. These complex pings are transmitted every few seconds by the pinger.

There are a number of advantages to this approach:

Lower frequencies allow superior acoustic penetration of the pipe wall and surrounding materials such as concrete weight casing, coatings and even soil. These lower frequencies also travel farther through open water, increasing the potential range of the system without requiring additional power from batteries.

Clever modulation of multi-frequency pings also enable a number of complex signaling, communications and noise tolerance advantages over traditional single tone signaling.

How Chordal Pings Combat Multipathing

But of great importance is a multi-frequency pings' effectiveness at combating the effects of multi-pathing. When the SeaTrack pinger emits its chordal ping, each of the 15 frequencies have different transmission coefficients. As these frequencies are reflected and refracted at the interfaces between mediums with differing transmission velocities, each constituent frequency reflects and refracts slightly differently than its neighboring frequency. Because of this effect, known as Snell's Law, the SeaTrack receiver hydrophone is guaranteed the arrival of some, if not all, of the chord's 15 frequencies.

Shown in Figure 4 is the SeaTrack deck box hardware - a ruggedized PC platform with a 17" touch screen graphics display. Currently attached is a towable receiver hydrophone and a GPS antenna.

Figure 4 - SeaTrack Deck Box, Towable Hydrophone with Rope Drogue

CDI's SeaTrack software running on this receiver computer is designed to be tolerant of signal loss. By default, SeaTrack can identify its unique chordal ping with as many as three of its constituent frequencies missing entirely, either lost to multipathing or destroyed by noise in the environment. In particularly noisy environments, this number can be adjusted upward, increasing the system's fault tolerance from its 20% default.

Signaling Using Chordal Semaphores

As mentioned, one of CDI's goals with the design of the SeaTrack system was the transmission of digital data from inside the pipeline to the deck of a ship. SeaTrack's robust chordal pings also allow for this through the construction of what CDI has termed "chordal semaphores".

By modulating the pings in a proprietary manner, the software constructs a semaphore database of dozens of discrete characters which can be used individually to signal conditions inside the pipeline to topside receivers.

The most basic use of chordal semaphores is to provide unique and unambiguous pig identification. Each SeaTrack pinger which is attached to a pipeline pig is assigned its own device ID. This device ID is contained and transmitted within each ping of the system. Therefore, when the deck box receives a ping from a SeaTrack pinger, it's actually a coded semaphore indicating the device ID of the pig to which it is attached. Pigs quite literally travel down the pipeline repeatedly broadcasting their unique identification semaphore.

Because of this, distinguishing between multiple pigs in a pipeline or multiple assets in a field is a basic and inherent function of the system.

In addition simple asset ID, the system has the capability of stringing together chordal semaphores into decodable sequences. These sequences can represent small amounts of digital data. This information can be sent by the inline pinger and received shipside by the deck box with the same fault tolerance discussed previously.

Information Types Supported by Chordal Semaphore Sequencing

The information transmitted within chordal semaphore sequences may be arbitrary, meaning that the pinger itself may contain analog sensors, such as pressure sensors, shock and vibration accelerometers, etc., and the changing analog values may be transmitted in near real-time to surface vessels.

In fact SeaTrack's chordal semaphores may comprise simple TRUE/FALSE state change information, such as the condition change of a gauging plate.

To better accommodate the demands of product customization, SeaTrack may also ultimately be used by clients to transmit arbitrary digital information from their own computer data systems through the use of an RS232 serial input. In other words, an intelligent inspection tool or seabed asset could use the system as a simple, but robust, acoustic modem.

Data rates are low, on the order of eight bits per second. However, for in situ pipeline monitoring and signaling this is typically sufficient. For high-speed acoustic transmission through water alone, many solutions exist.

Doppler Measurement and Resolution

Another goal of the SeaTrack project was to provide a pig's speed from shipside.

Since each of the 15 frequencies of the pinger's transmission are known precisely, Doppler Shift measurements may be performed by the deck box software. These Doppler Shift calculations result in a speed representing the radial velocity of the pig versus the measurement platform.

In the simplest example, that in which a stationary vessel is positioned directly over a pipeline, the pig's approach and retreat speed can be known.

In Figure 5, SeaTrack's deck box software displays the target asset's speed to the operator. The proprietary algorithms which CDI uses to perform this Doppler measurement are accurate to within 1/3 of a knot, or about 1/2 of a meter per second. This image shows a system which has detected Chord 2, that the pig's measured Doppler radial velocity is 2.4 knots, and the signal to noise ratio of the ping is 9.8dB.

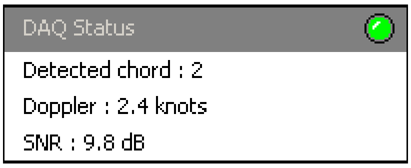

Figure 5 - Doppler Speed Display

There are many possible uses for knowing a pig's speed from the vessel. The most basic use of Doppler speed information is to know quickly whether in fact the pig is moving at all, or is stationary, perhaps stuck. Arrival into a subsea pig receiver may also be detected, as the pig's speed will, of course, drop to zero.

Because of the Chordal construction of SeaTrack's pings, Doppler measurements are considerably more accurate than those that could be made with pings of a single frequency. Given that a single frequency ping provides only one frequency data point for comparisons, the signal to noise level at the receiver will need to be quite high to achieve an acceptable level of accuracy. Increasing the signal to noise level at the receiver for single frequency systems involves increasing pure output power beyond these systems' already high levels, but the problem of multipathing persists.

Pig location Using Doppler Inversion

Since, through Doppler measurements, radial velocity of the pig versus the measurement platform can be known, it is also possible to move the vessel relative to a stuck or stationary pig and locate that pig using Doppler information created by the vessel's movement. CDI refers to this technique as Doppler Inversion.

With Doppler Inversion, a towable hydrophone is deployed behind a work vessel and towed. As the vessel is moving relative to the pinger, Doppler shift information is created. If the vessel is underway at 5 knots and the measured Doppler is 3 knots, it can be known that the heading to the pinger is not correct.

SeaTrack's deck box is GPS equipped and, therefore, constantly knows its own velocity on the surface of the water. By comparing the known GPS velocity and the calculated Doppler speed, SeaTrack measures and displays the angular difference between the two.

There are two possible solutions for this angular difference, one to port and one to starboard. If the Doppler measurements are positive (i.e. the frequency of the chordal pings has been upshifted), SeaTrack knows and displays that we are moving toward the target. If the Doppler measurements are negative (the ping frequencies are downshifted) SeaTrack displays that we are moving away from the target.

Through simple trial and error, the captain may maneuver the vessel until the measured Doppler matches that of the vessel's speed. When this is achieved, a bearing to the stationary pinger has been ascertained.

If one achieves this bearing and continues along the course, eventually the target will be overrun. As the vessel approaches the target, the Doppler will begin to downshift, with the rate of downshift dependent upon the water's depth.

SeaTrack's deck box software monitors this Doppler downshift, and when the measured Doppler inverts, or switches from positive "approaching" Doppler to negative "retreating" Doppler, SeaTrack drops a GPS waypoint on the screen showing the estimated location of the stationary pig as shown in Figure 6.

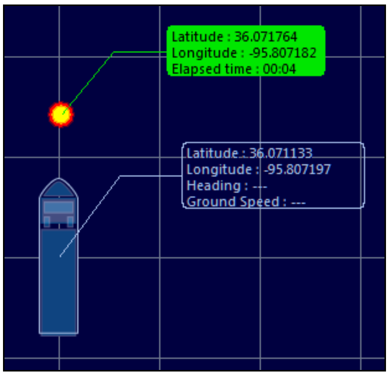

Figure 6 - Estimated GPS coordinates of pinger (yellow point) based upon Doppler Inversion technique. Vessel position also shown.

Doppler inversion is particularly well suited to the case where the route of the subsea pipeline is known, as it often is. This allows for quick resolution of the bearing to follow as it is simply the path of the pipeline. Doppler inversion, however, still reveals the location of the stationary pig as a GPS coordinate. Again, this behavior is achieved without deploying either divers or ROVs.

Pig location using Cooperative Target Motion Analysis

One of CDI's most ambitious goals with SeaTrack was the continuous, near real-time tracking of a moving pipeline pig from a moving vessel.

In order to achieve this goal SeaTrack has implemented a technique most often associated with military submarine combat technology: Target Motion Analysis.

Simply stated, a submarine uses Target Motion Analysis to determine the course, speed and position to an unknown acoustic source. A submarine is fitted with arrays of sensors including a towed array which is deployed behind the submarine to listen for acoustic signatures in the environment.

The submarine sensor arrays can determine the angle of arrival, or bearing, from which the acoustic energy arrives. With only this information however the target can lie at any point along the observed bearing line, that is, there is a large number of possible "solutions" to the problem of "where is the target".

By maneuvering the submarine in a pre-defined manner and observing changes in the bearing of the target over time, the number of solutions can be greatly reduced and eventually the correct solution to the target's course, speed and position can be determined using complex mathematics and some degree of intuition and experience.

SeaTrack simplifies the problem of TMA and makes this technique available to the less skilled user by using CDI's "Cooperative Target Motion Analysis" (CTMA) technique, in which the system uses its knowledge of the transmission characteristics, and the automatic readout of Doppler and GPS information provided by the SeaTrack receiver, to provide simple and effective TMA suitable for use with little operator training.

In Figure 7 are shown a series of images illustrating the results of SeaTrack's Cooperative Target Motion Analysis on a lake in Oklahoma. The green "X" represents SeaTrack's estimated location of the pinger on the lake bed. The red dot near the bottom is the true location, and the dashed lines represent data sample points over time. In this image the estimated location of the pinger is within a few meters of its true location whenever data points from at least two legs of the vessel's course are included in the calculations.

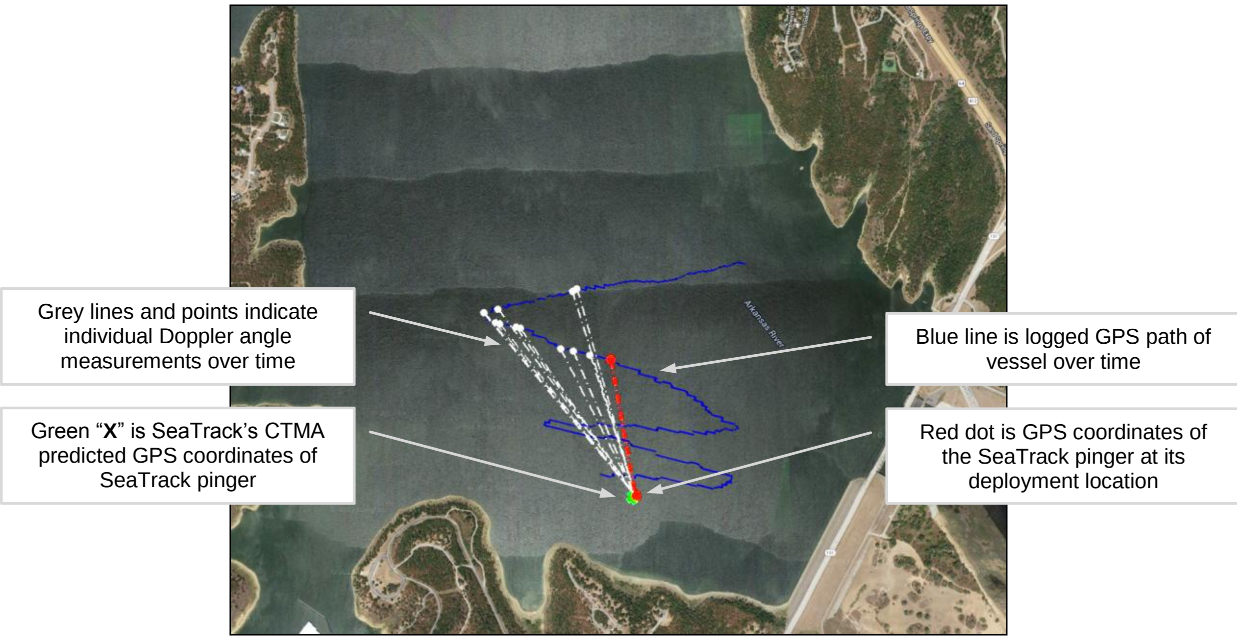

Figure 7 – SeaTrack TMA Example

SeaTrack's CTMA algorithms take this into account, and regardless of the length of each leg of travel maintain at least two of the most-recent data points from the previous leg. As this data ages, however, the CTMA solution estimate degrades. Therefore, for best results the vessel must make at least slight course changes every few minutes, with best results from course adjustments of a full 90 degrees.

As can been seen, the deck box software has integrated GPS positional data, allowing for the overlay of our acquired data with a map of our Oklahoma lake. The estimated CTMA GPS position of the target pinger is obviously known.

In this instance, the target was stationary, however, tracking a moving target is also possible. Vessel velocity and position as measured through GPS must be accounted for versus our Doppler measurements to produce correct results.

CDI continues algorithm and software work in this area, and expects to have results in the spring of 2014.

Conclusion

In conclusion, Acoustic pig and asset tracking is capable of far more than is currently being delivered by vendor companies and at much higher reliabilities. SeaTrack's capabilities, as developed by CDI, provide pipeline operators with a large toolbox of techniques to track, locate and communicate with their inline assets whether they are moving or stationary.

These techniques, some of which are mathematically complex to automate, are nevertheless well understood and relatively easily tested.