Low Profile Cranes
An Introduction

PEMA Autumn Meeting
October 2023

Steven Martinez, ME, PMP
Senior Associate
Liftech Consultants Inc.
www.Liftech.net

Good afternoon. This is the first PEMA event that I have attended, and I am thankful for having the opportunity to speak with you today on the topic of Low Profile Cranes.

My name is Steven Martinez. I am a mechanical engineer with Liftech Consultants.

Jonathan Daniels is presenting next. His low profile cranes at Port Everglades are featured throughout this presentation. We value our partnership with Port Everglades and the trust from Broward County.

We also appreciate having Port of Virginia in the room, who is also procuring low profile cranes.

About Liftech

Liftech's founder, Mike Jordan, was a structural engineer in the early days of the crane industry. He designed the structure of the first container crane in 1958 and later founded Liftech.

We are based in Oakland, California, with a satellite office in Shanghai, China. Liftech has grown from a structural engineering firm to a full-service engineering consulting firm with structural, mechanical, and electrical engineering services.

Our focus remains on ports, including cranes, wharves, floats, voyage; crane-wharf interface including seismic and hurricane designs; and electrification.

Agenda

Overview

Structural Considerations

- Truss boom
- Wheel loads
- Lateral loads
- Analysis

Mechanical Considerations

- Gantry positioning
- Gantry drives
- Variable torque braking
- Headblock nesting
- Saddle machinery house

Electrical Considerations

- Anti-collision
- Trolley-boom synchronization

3 of 29

Liftech
LIFTECH CONSULTANTS INC.

This presentation is organized into four parts:

The Overview is exactly that, an overview of generalities about low profile cranes. We will address the basic questions of, "What is a low profile crane?" and "Why are they necessary?" We will discuss some general parameters and constraints of their design.

In Structural, we will give an overview of some of the key structural elements of low profile cranes and how they are unique. The focus will be on the four points you see here: Truss Boom, Vertical Wheel Loads, Lateral Loads, and the structural analysis we perform.

In Mechanical, we will introduce some of my favorite topics of low profile cranes. The first three bullet points are all related to the gantry (wharf level) systems of the crane, as the crane gantry has had to have a lot of specific development for low profile cranes: Gantry Positioning, Gantry Drives, and Variable Torque Braking. We will also cover headblock nesting, and the saddle machinery house, which are features to maximize clear under spreader height.

In the final section, Electrical/Controls, we will cover two topics: the anti-collision systems on low profile cranes, and trolley-boom synchronization.

Overview

Purpose

Overview

Why a low profile crane?

To satisfy airspace/flightpath regulations - FAA Obstruction Evaluation Airport Airspace Analysis (OE/AAA 7460)

5 of 29

Liftech
LIFTECH CONSULTANTS INC.

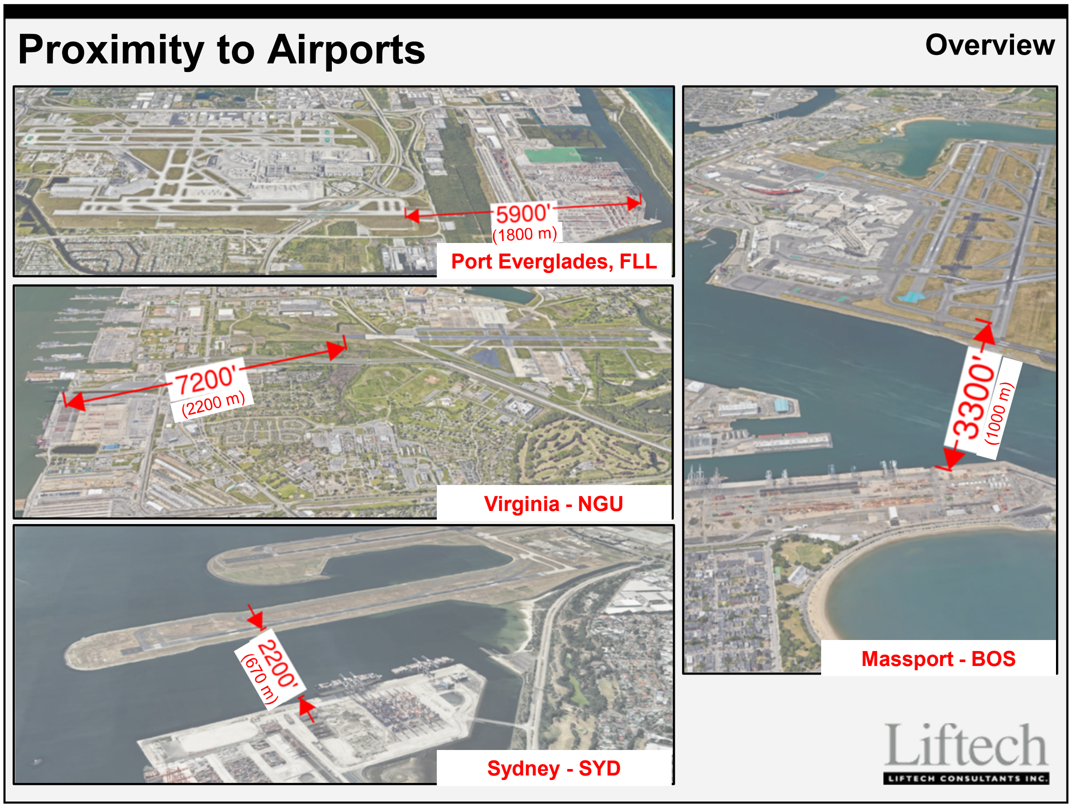
The first question is: Why do we need low profile cranes? The answer is shown in this cool picture taken while standing on top of a low profile crane in Boston, Massachusetts, aka Massport.

The purpose of low profile cranes is to satisfy airspace/flightpath regulations when the container terminal is in close proximity to airports.

In the United States, we have the Federal Aviation Administration, the FAA, who has jurisdiction to set the aircraft minimum clearance envelopes for approaches and departures.

In general, the clearance height is not a single number, but a 'cone' in 3-D that extrudes from the runways. Notice on later slides that we push the limits of this cone, sometimes sloping the profile of the crane to just meet the cone envelope.

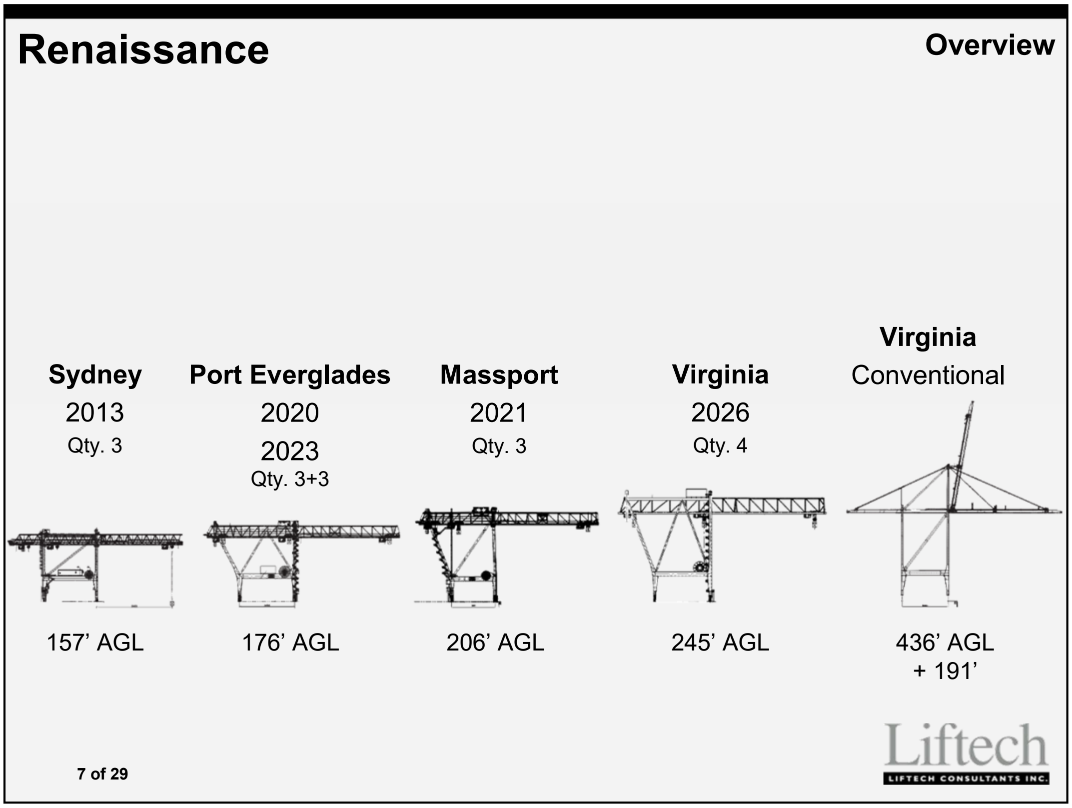
All low profile crane project engineers must work with the airspace regulatory body to establish allowable heights.



Here are a series of aerial images for low profile projects that we have recently done. These images give an impression of the proximity from the container terminal to the runways.

For example, in the upper left image, note that the Port Everglades terminal is within 5,900 ft (1,800 m) from the leading edge of the runway.

Other projects vary in approach angle and distance from their respective runways, which, as the next slide shows, has a direct effect on the ability to set the height of the crane.



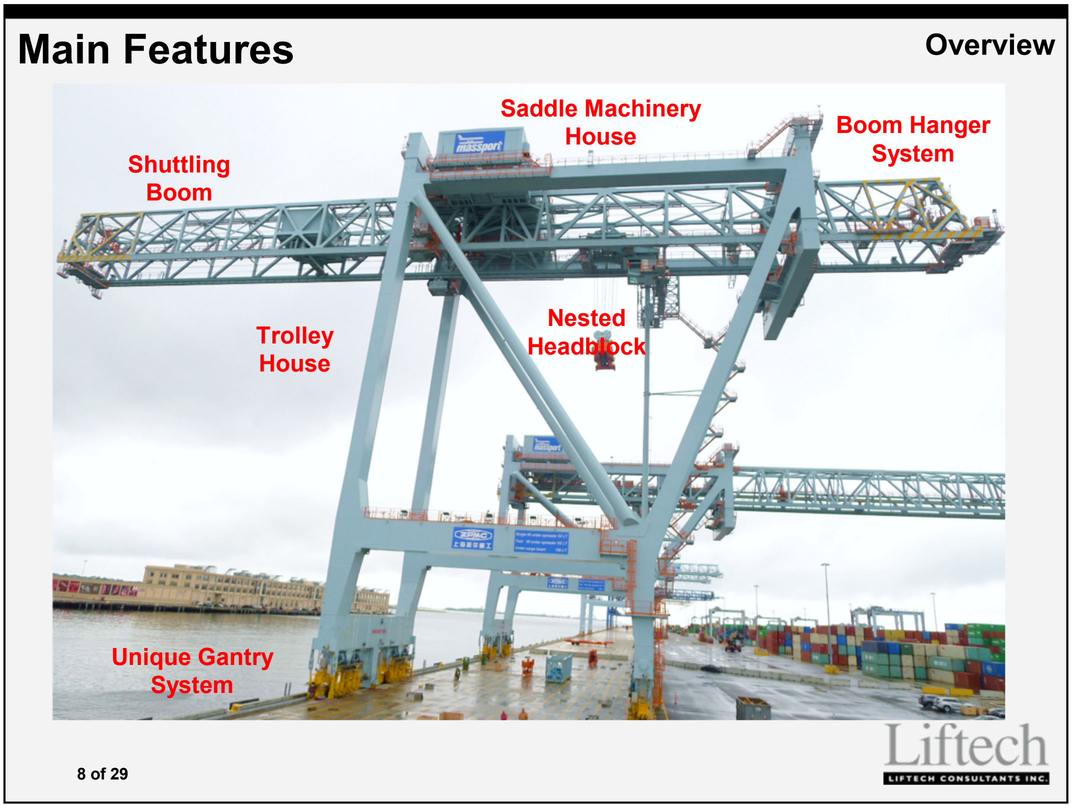
During the last ten years, Liftech has seen a resurgence in the procurement of low profile cranes.

This diagram represents our four most recent low profile procurement projects with a conventional crane included for comparison. The AGL number under each image is the overall maximum height of the crane “Above Ground Level.”

Sydney, Australia; Port Everglades, Florida, with two successive procurements; Massport in Boston; and now an ongoing project with Virginia that is currently in the design stage.

Notably, ZPMC manufactured all of these cranes. ZPMC has been a good partner with us for these low profile crane projects.

Note the two Virginia cranes on the right. The conventional STS crane has the same lift height and outreach as the low profile crane next to it. Notice how the design saves approximately 191 feet in above ground clearance



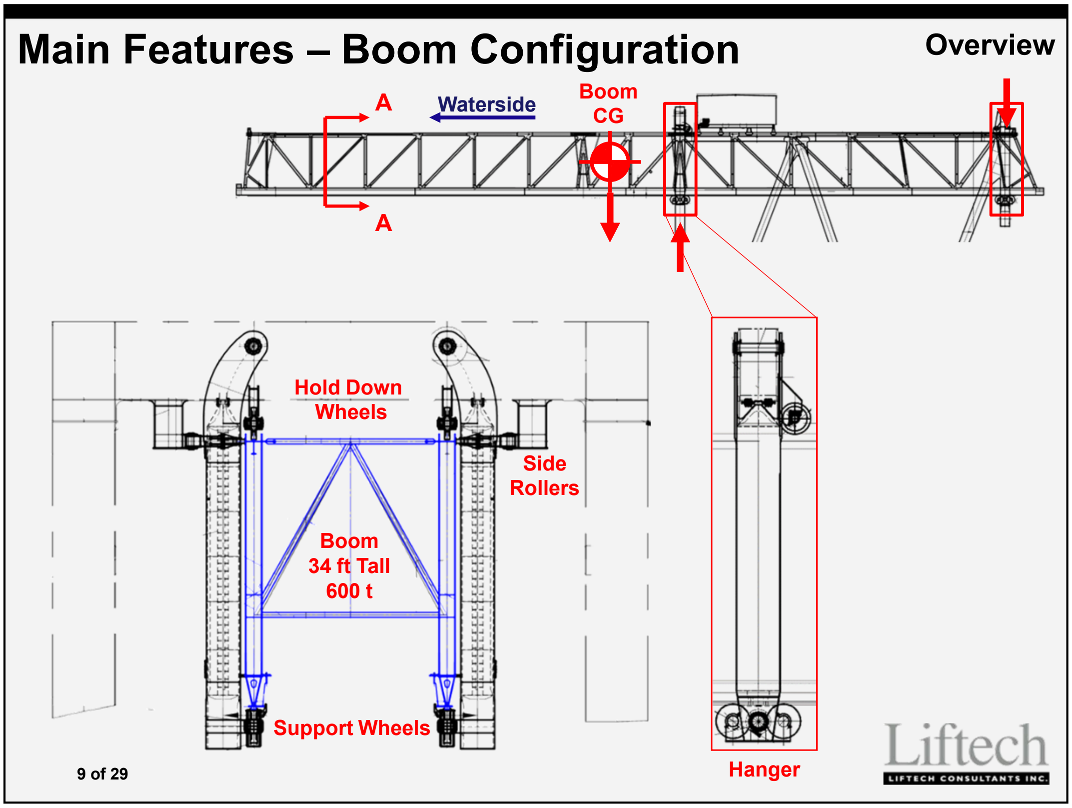
This is a photograph of the Massport cranes, with some annotations for the main features of low profile cranes.

The main difference between a conventional A-frame crane and a low profile crane is the upper works area.

The low profile crane uses a shuttling boom that extends and retracts, rather than rotating about a hinge. The boom is a deep truss structure that provides the necessary rigidity without forestays and boom ropes as support.

There are two cranes in the image. The foreground crane shows the boom almost extended, while the background crane shows the boom in the retracted position.

The machinery house is what we call a saddle machinery house. The trolley machinery can be separate from the main machinery house and rides on the boom itself. Ability to nest the headblock increases lift height. The cranes also have a unique gantry system. The remainder of the presentation will discuss these areas in more detail.



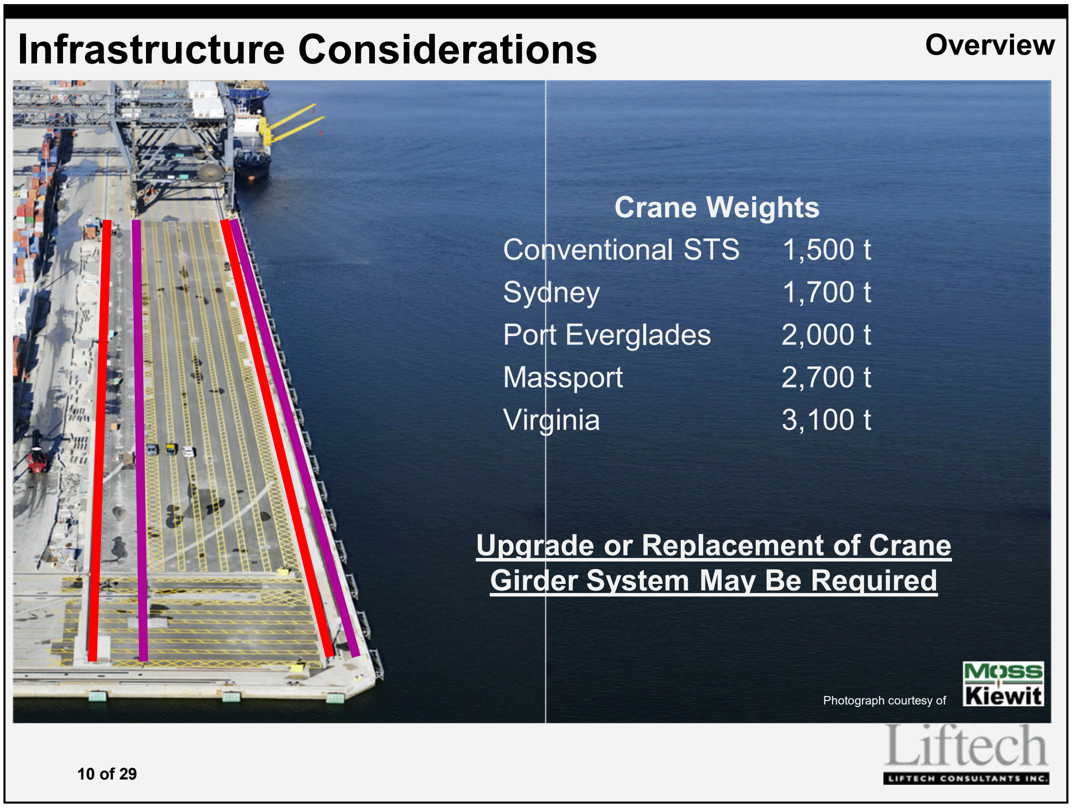
Let's get into the boom and hanger system in a bit more detail.

Here we have three images. The top image shows the side view of the boom. Note that the boom center of gravity (CG) is cantilevered; it is beyond the hanger support. The same is true when the boom is fully retracted . That CG moves behind the other support. That is to say that the boom actually teeter-totters as it shuttles and must be supported on its topside with hold-down rollers.

The image on the bottom right is a zoomed in view of the waterside hanger. The hangers are the main boom structural support. There are many design features of the hanger that we do not have time to describe in this presentation, but notice the support wheels on the bottom side, as well as the hold-down roller on the topside. These wheels and rollers encounter heavy loads and are 1,200 mm to 1,300 mm in diameter.

The bottom left image shows the cross section through the boom (with boom in blue) at the waterside hanger location. Note that the hangers on the waterside are pinned connections to the structure to accommodate deflections. Boom lateral loads are resolved using side rollers at the boom top chord. The landside supports are somewhat different than the waterside, as they are on a fixed beam.

For a sense of scale, the boom at Virginia Port Authority is the biggest and heaviest yet. It is 34 ft (10.4 m) deep and weighs 600 tonnes. It is a large moving load.



Infrastructure Considerations. Low profile cranes are significantly heavier than conventional A-frame STS cranes, for a given outreach and lift height.

While a large conventional STS crane weighs up to 1,500 tonnes, even a relatively small low profile crane will weigh over 10% more, at 1,700 t.

Port Everglades is at 2,000 t, which we thought was a lot at the time, until we moved onto the Massport project at 2,700 t, and now Virginia, which will weigh over 3,000 t. We believe it is the heaviest container crane in the world by far, a dubious honor.

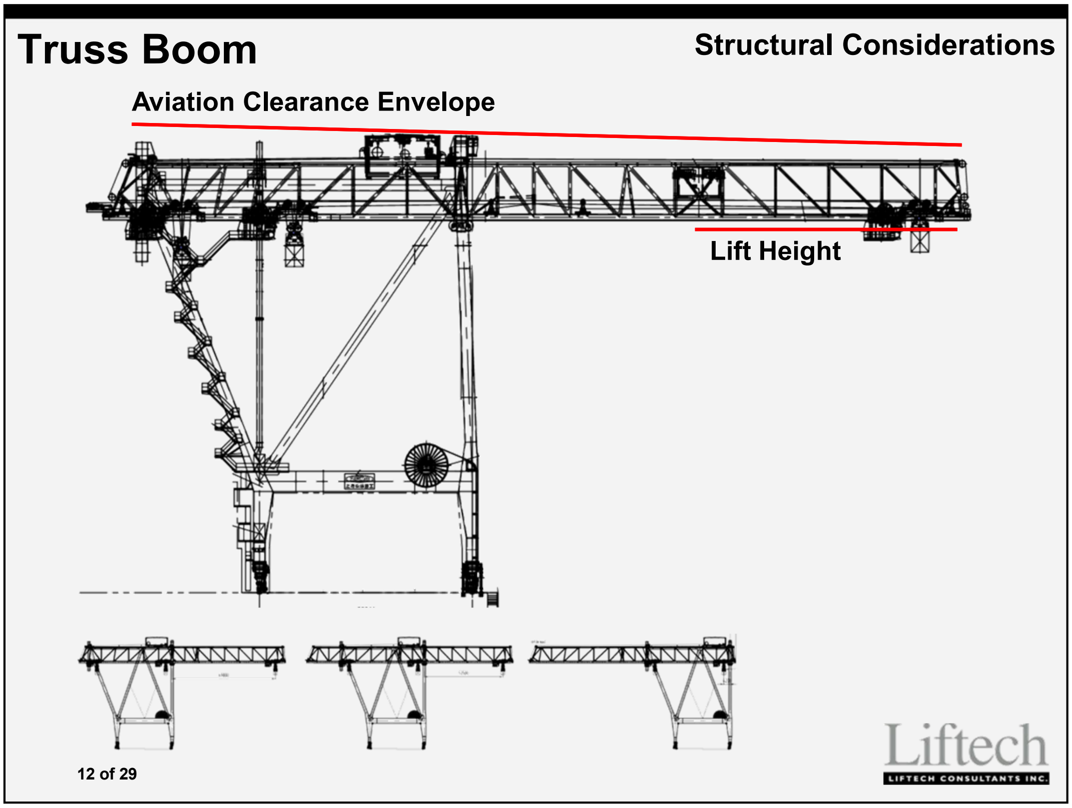
For example, see this image of Port Everglades Berth 30 where they already have older Samsung low profile cranes that use the rails colored purple. For their new procurement, we had to install additional waterside and landside girders with a wider rail span.

A significant portion of the weight of low profile cranes is ballast weight put into the sill beams (400 t to over 550 t). This is necessary for crane stability.

We cannot expect low profile cranes to be compatible with existing wharves, which have significantly lower girder and rail capacity than required. The piles, girders, rails, and rail gage need to be upgraded or replaced.

Structural Considerations

Moving into Part 2: Structural Considerations



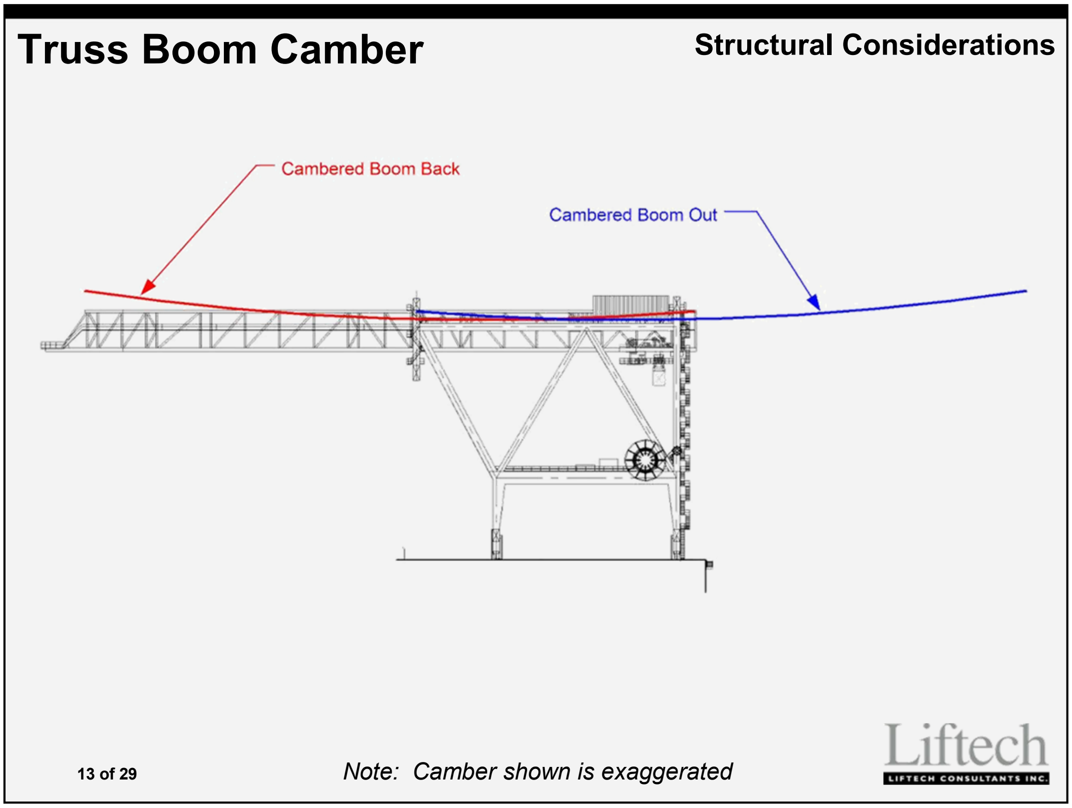
We already discussed the truss boom, and here are a few more points.

The profile of the crane is designed to be near the absolute maximum aviation clearance envelopes. Sometimes, the clearance line is sloped in the opposite direction, where the airport is aft of the cranes.

Look at the sloping line and compare it with the spreader lift height of the crane. The depth of the boom is the primary element of the crane that governs the lift height, so it is critical to design the boom efficiently. The boom depth needs to balance stiffness with the lift height.

As such, the boom depths will vary significantly with the desired outreach.

For example, Port Everglades with a 62.5 m outreach has a boom depth of 24 ft (7.3 m), while Virginia, with an outreach of 69 m, 6.5 m longer or about 2.5 containers, has a depth of 34 feet (10.4 m), nearly 10 ft (3 m) deeper for only about 2.5 containers of added outreach.



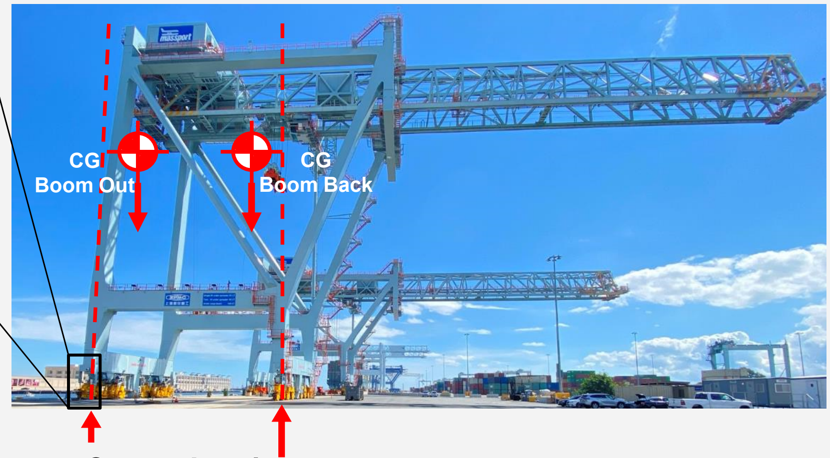
One method we developed to maximize the efficiency of the boom is to design and fabricate the boom with a camber. The boom is fabricated with an upward radius shown in the image, so that when it is erected on the crane, its dead weight makes it lay flat.

To control the deflection during fabrication, the chords are fabricated straight, then those chords are set into a jig to obtain the correct camber shape, and then the diagonal trussing is welded in. There is minimal internal load; the jig jacking forces are only about 1 tonne per jack.

Wheel Loads

Structural Considerations

**Massport
Two Tie-Downs on Waterside**



Corner Loads

	WS	LS
Retracted	250 t	1,100 t
Extended	1,000 t	350 t

4:1 Max/Min Wheel Load Ratio

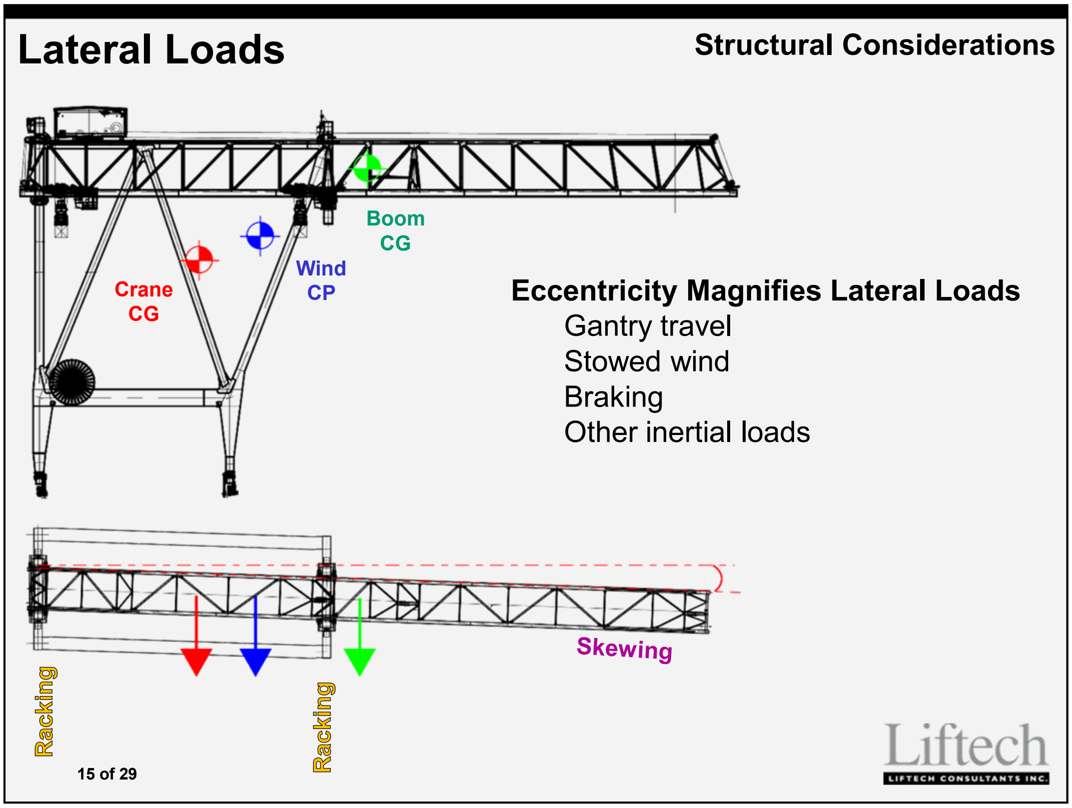
14 of 29

Down at the gantry level is where it gets interesting, when we talk about wheel loads. The boom is approximately 40% of the total crane weight. Recall from a previous slide that the boom CG is eccentric to the support hangers. In terms of total crane weight, the photograph roughly shows locations of the total crane centers of gravity with the boom out and back. Notice how it shifts when the boom moves from its extended position to its retracted position.

The table quantifies an example of corner loads. Simply based on the boom position, the basic corner loads can vary by 750 tonnes, so the wheel loads vary by a 4:1 ratio from maximum to minimum.

This 4:1 ratio does not account for our many design cases that include other eccentric loads, such as for the trolley, lifted load, and wind, that make the wheel load ratios even more extreme.

For example, see the image to the left showing the storm tie-downs at Massport. Massport has a storm design condition where there is significant uplift at the corner--enough to warrant a double tie-down on the waterside.



The previous slide introduced the basic vertical loads. This slide focuses on the lateral loads on the crane that influence the design.

Using this image of the retracted boom , we show three fundamental work points: the overall crane CG in red, the center of pressure of wind in blue, and the boom CG in green. Notice how eccentric these points are, relative to the centerline of the crane between the gantry rails.

The eccentricity of these points means that lateral loads are significantly amplified when resolving these lateral loads at the gantry level.

When the crane travels down the wharf, the lateral forces can be heavy, particularly in the deceleration design cases, such as braking and collision loads.

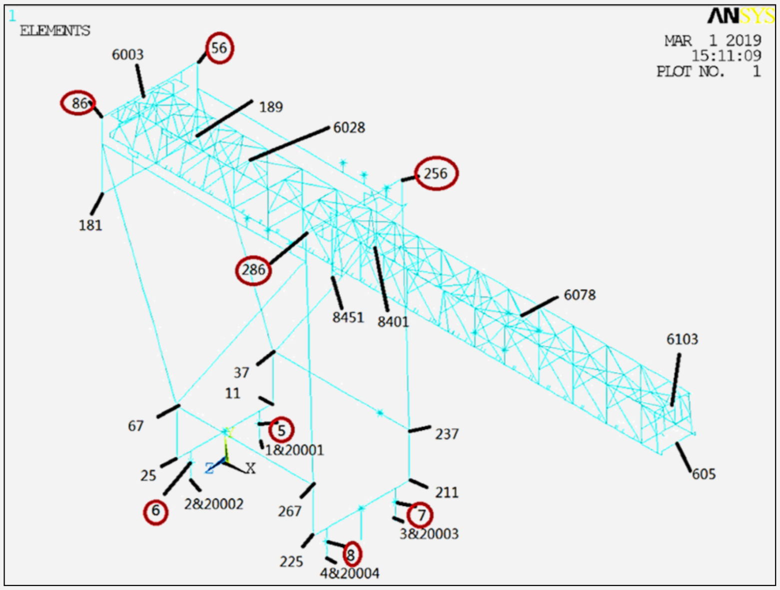
Wind loads, such as operating and storm conditions, impose very asymmetrical loads on the crane.

Due to these forces, the crane is displaced laterally in two different ways, which we describe as racking and skewing. Racking is a parallel type offset between the waterside and landside gantries. Skewing is a rotation of the crane and boom.

Racking and skewing are undesirable, as they have a negative influence on the stress levels of the crane, as well as the crane geometry. These factors need to be considered in the design.

Analysis

Structural Considerations



A Lot of FEA and Time History Analysis

16 of 29

Liftech
LIFTECH CONSULTANTS INC.

There is a high level of analysis required for reviewing these low profile crane projects. The loads are significantly heavier than conventional STS cranes, there are added operational load combinations due to the different operational positions for the boom, and the inherent eccentricity of the design across many load combinations creates a variety of problems. There are also many more structural members and connections on this type of crane.

We must perform a significant amount of structural review and use finite element analysis (FEA), time-step analysis, and data point monitoring to evaluate overload conditions and potential points of high stress. For example, this image shows some of the nodes were tracked, and the circled nodes represent the nodes that were monitored more closely due to their sensitivity.

To briefly mention design standards that we use: for structural design, we use ASCE 7 loads and load combinations for wind and seismic. We use ASD level expected loads and combinations for the operational and other overload conditions.

Mechanical Considerations

Section 3: Mechanical Considerations

Gantry System

Mechanical Considerations

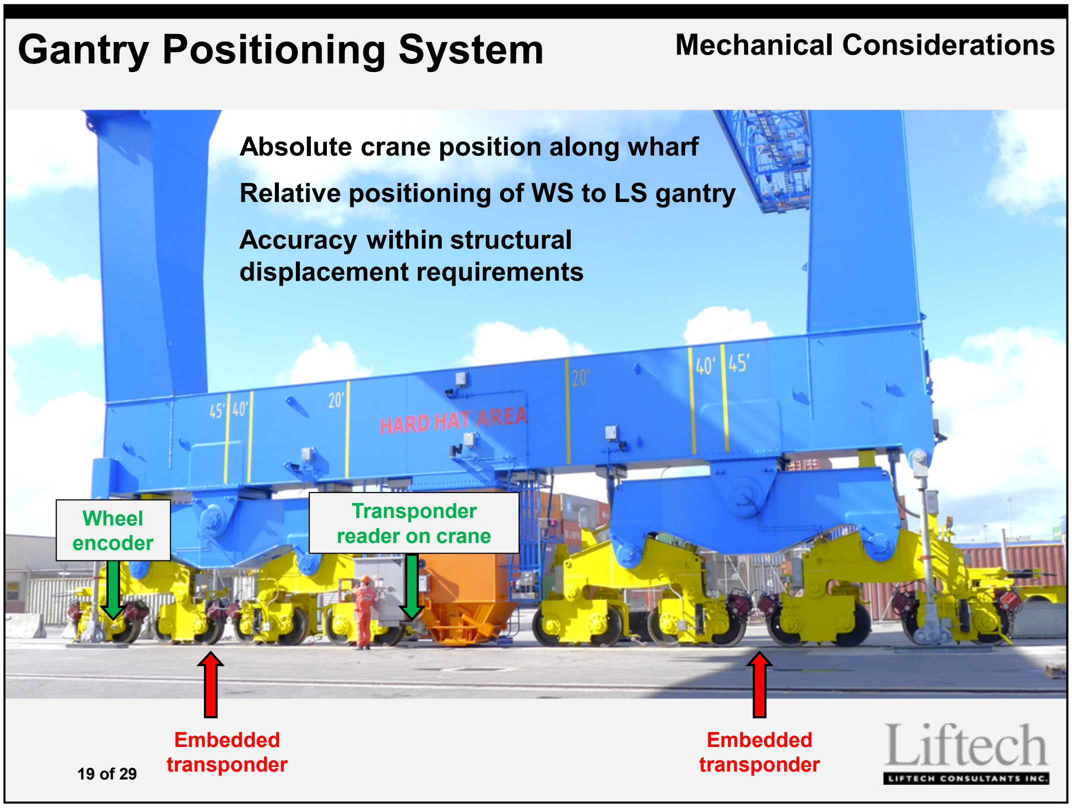
Unique Gantry Features

- Transponder-based positioning system
- Higher capacity gantry drives
- Variable torque braking

Liftech
LIFTECH CONSULTANTS INC.

As mentioned in the Overview section, several of the mechanical slides are devoted to the gantry system. The next few slides will focus on three key areas:

- Transponder-based gantry positioning system.
- Gantry drives themselves, and how their design capacity is distinct from conventional STS cranes.
- Variable torque braking - A topic that was pioneered for low profile cranes, not to be confused with antilock braking (ABS) like in your car.



Gantry Positioning System

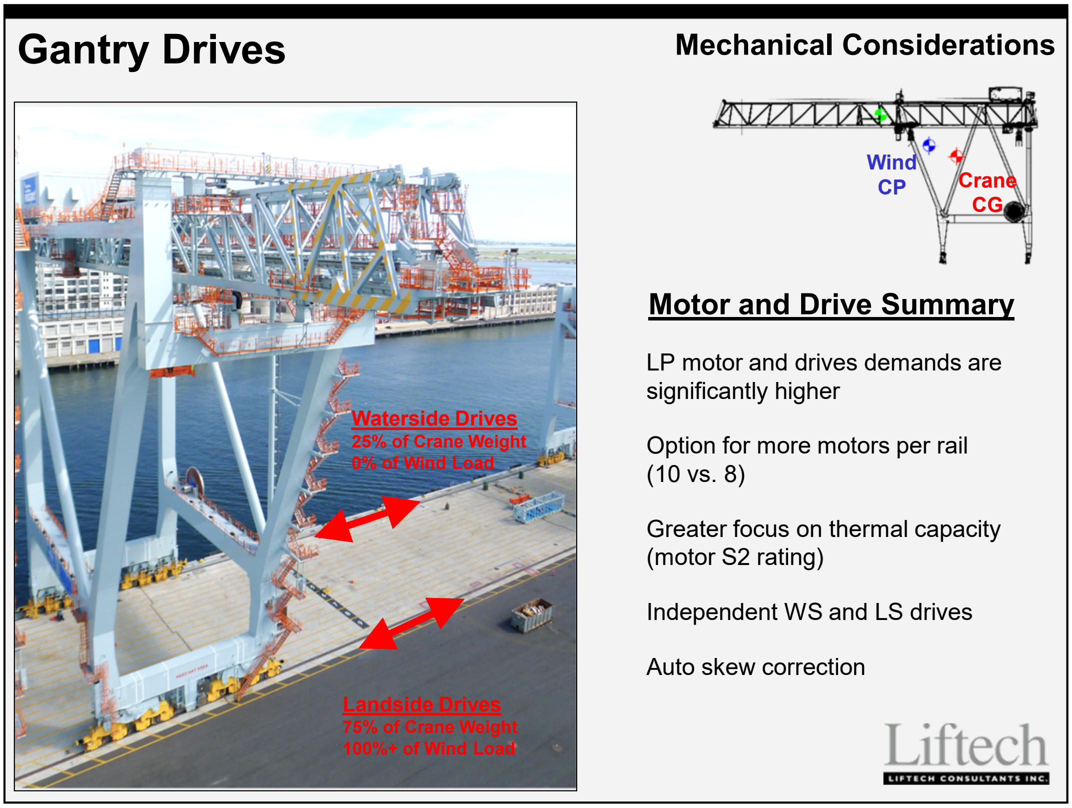
Several slides ago, we briefly touched on Racking and Skewing, which are two undesirable modes of displacement of a crane, and how they negatively affect the crane structure.

It is critical that we needed to develop crane features to actively monitor and correct these conditions. We target approximately 1 inch (25 mm) of allowable racking, which cannot be achieved unless a closed-loop system of feedback and active correction was developed.

We worked with the crane manufacturer and drive suppliers to develop a more advanced gantry positioning system. Traditional STS positioning systems are used for crane positioning only along the length of the berth, and are typically referenced only on one of the two rails, either waterside or landside.

These low profile cranes use transponders embedded into the wharf on both waterside and landside rails. Note the red annotations that provide the approximate transponder spacing embedded into the wharf.

There is also an encoder on one of the wheels for reach rail of the gantry. The wheel encoders provide an accurate distance count, which is validated and recalibrated by the transponder system. The waterside and landside are continuously compared, and any asymmetry is corrected automatically by the drives.



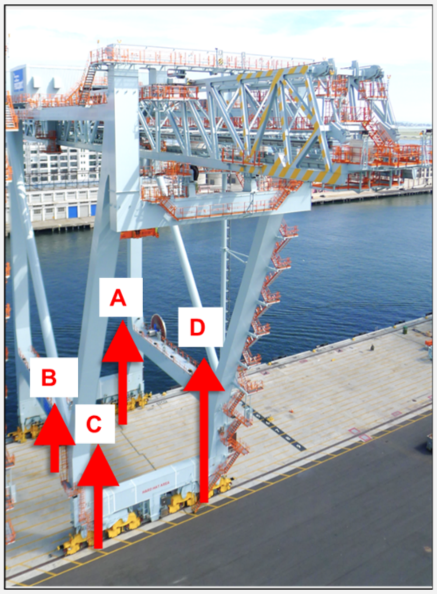
In the upper right image, recall from the earlier slide the positions of the crane center of gravity. The wheel load ratio of 4:1 is equivalent to the ratio of power that the crane drives need to deliver to overcome inertia. For example, with the boom retracted, the landside needs to deliver four times the torque as the waterside to stay the same acceleration ramp. Likewise, when the boom is extended, the ratio is inverted. This ratio is significantly higher than for a conventional STS crane.

Now recall the position of the wind center of pressure (CP), noting that the wind load resolves slightly aft of the landside rail. Those of you who like free body diagrams will see because the wind CP is behind the landside rail, the wind is trying to make the crane spin or pivot about the landside rail, and there can be more that 100% of the crane's wind load that the landside gantry motors need to drive against, by themselves.

When adding up the inertial demand plus the wind demand together, the low profile gantry motor demands are significantly higher than would otherwise be if the crane were more symmetrically loaded. We resolved this issue through brute force by upsizing the motors, drivetrain, and drives, but also through efficiency by more rigorous review of the thermal capacity of the motors and relying on the S2 duty cycle rating of shorter intervals of the motor rather than the S1 continuous rating.

Note also that the WS and LS drives are independent, so the racking and skew correction commands are executed by the drives to speed up or slow down to keep the crane square.

Variable Torque Braking (VTB) — Mechanical Considerations



Brakes rely on available traction

- High brake torque and low corner load will skid
- High brake torque with high traction will have rapid deceleration

Skidding

- Damages wheels
- Racks the crane
- Reduces stopping capacity
- Loses absolute position

Excessive torque

- High lateral G forces
- Crane racking/skewing

VTB solution

- Inputs: boom position, wind parameters, trolley position and load
- Identifies a configuration
- Outputs: brake thruster voltage proportional to desired torque
- 0% to 100% torque range, variable on per corner

21 of 29

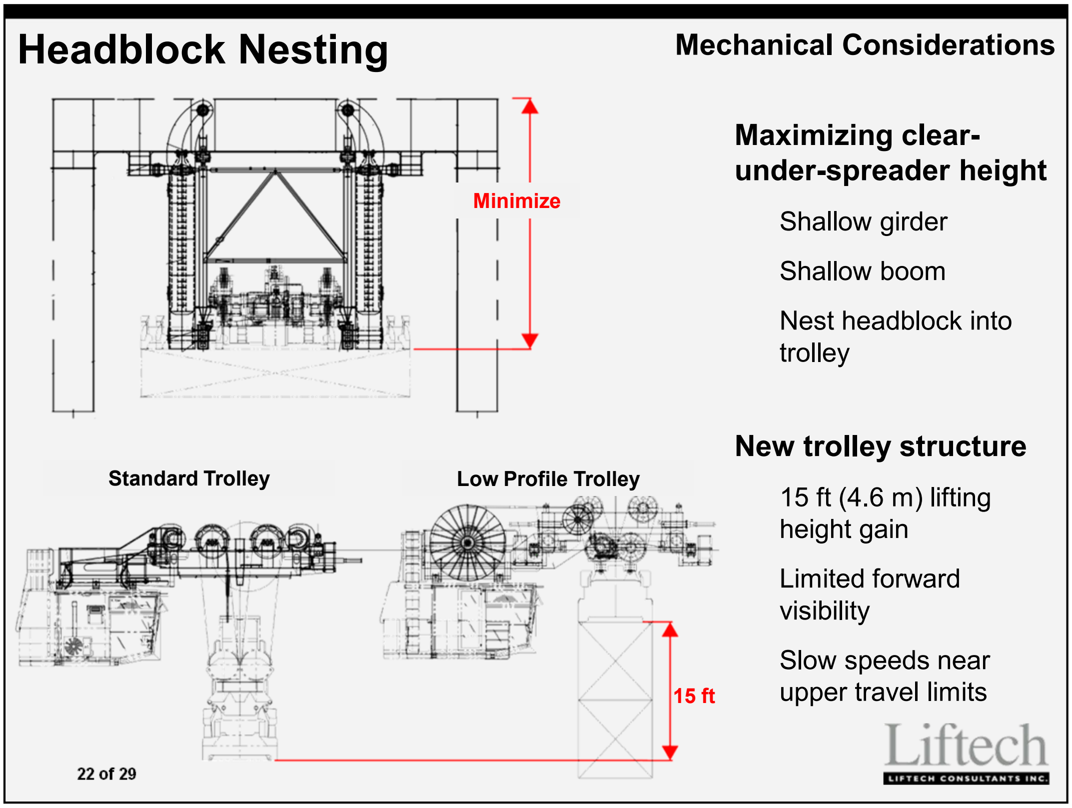
Due to the crane vertical loads and the lateral loads, the traction available at each gantry corner varies widely. As labeled here, corners A,B,C,D can have from as little as 0% load, and up to 40% of the crane weight as traction, depending on the crane conditions.

Brakes are limited in their ability to perform by the traction available, and excessive torque will skid the wheels. Skidding not only increases stopping distance, it damages wheels, racks the crane, and may also lose the measured crane position. Conversely, applying excessive stopping torque will cause high gantry lateral forces that propagate throughout the crane and will also rack and skew the crane.

We worked with ZPMC and Bubenzer brakes, along with the drive suppliers ABB or TMEIC, to develop variable torque braking (VTB). It is a braking system that varies the voltage value to the brake thrusters at a precise value to partially retract the brake thrusters, applying a partial torque.

VTB is summarized as follows: the crane monitors the parameters that are sensitive to wheel loads, which are boom position, wind speed and direction, trolley position, and lifted load value, and uses these combinations to reference a pre-built state table of known desirable brake torques at each corner for that configuration. The crane loads and stores the state table in anticipation of an emergency braking event. The crane refreshes the state table whenever the parameters change.

Note there is no skidding feedback like true ABS, so we tend to conservatively build the state table to avoid potential for undesirable lat-g forces and skidding.



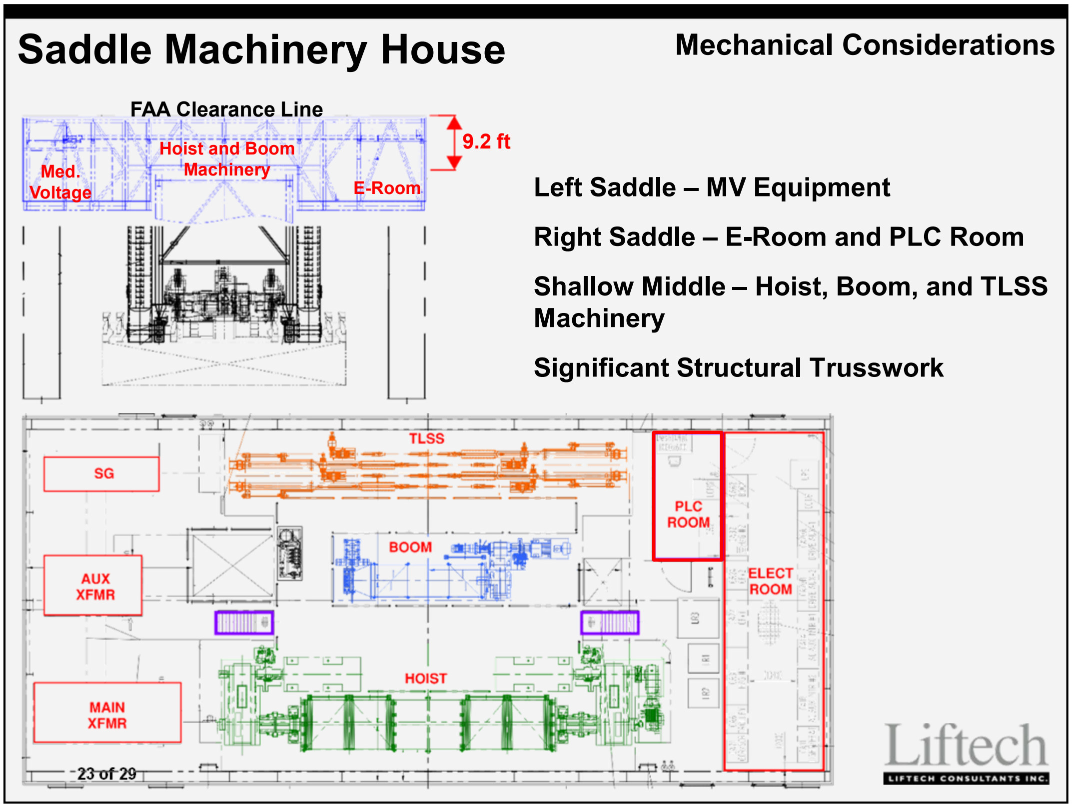
Now we will move on from the gantry and look at the trolley, which is unique for low profile cranes to maximize lift height.

The top image again reminds us of the goal with low profile cranes, which is to maximize the lift height, by minimizing the dimension shown, which is the distance from the bottom of the spreader to the top of the structure.

We maximize the lift height through changing the depth of the cross beam, the depth of the boom, and designing what we call a nested trolley.

The nested trolley can provide up to 15 ft (4.6 m) of additional lift height compared with a conventional STS trolley, which is almost two containers of lift height. This is achieved through a new trolley structure where the headblock intrudes into an opening in the trolley, and the sheaves are close together.

There are some limitations and compromises to this design, which make it undesirable for conventional STS cranes: Visibility is limited, making it necessary to rely on forward facing cameras, and there are additional interlocks and slowdowns when the headblock enters the overlap zone with the cabin, to prevent interference with the trolley.



In that slim area between the top of the boom and the top of the crane, we need to package and house the machinery for the main hoist and for the boom shuttle. The total height in that area is only 9.2 ft (2.8 m), and needs to consider the service crane, cable runways, etc., and the structural foundation. This height constraint necessitated a unique machinery house design that required some creative structural, mechanical, and electrical solutions.

In the top image, the profile of the machinery house is a saddle and uses a truss structure instead of a traditional flat machinery deck. The truss is necessary for stiffness because the machinery house is the full width of the crane, supported only at the outer edges. Typical STS machinery houses are narrower and have the supports much closer together.

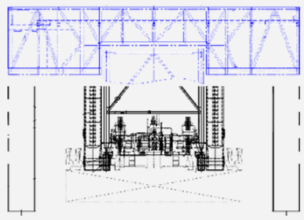
The hoist machinery (in green) is unlike a conventional hoist, since the drum length is long and spans across the width of the boom. The reducers and motors are tied into the deeper section of the machinery house saddles.

The purple-colored rectangles indicate stairways to walk up and down the saddle. The snag system (orange) is inside of the machinery house.

About the saddles. The left side saddle houses the switchgear and transformers. The opposite saddle houses the electrical room and PLC/CMS room.

Saddle Machinery House

Mechanical Considerations



24 of 29

Liftech
LIFTECH CONSULTANTS INC.

Here is a better view of the saddle machinery house for the Massport cranes.

The lift heights that we achieve with such a slender profile could not be achieved without a saddle machinery house.

At project inception, when we are writing the specifications, it takes a lot of upfront design work and iteration to develop and specify a lift height that is achievable for the contractor's design for a given aviation clearance envelope.

Electrical Considerations

Our final section, Electrical Considerations. I use the term electrical loosely, as this section became a catch-all for a couple of items that I didn't mention earlier. The topics are more about combined electrical/controls considerations.

Anti-Collision Systems

Electrical Considerations

B30-B31 Corner at Port Everglades

Anti-collision Systems

- Gantry transponder
- Gantry laser
- Boom shuttling laser
- Boom lateral laser

26 of 29

As previously mentioned, the gantry transponder/encoder-based system has multiple functions. It is also used as a crane position monitor to the terminal operating system, in terms of avoiding crane-to-crane interference. The image above shows Port Everglades at their perpendicular Berths B31 and B30.

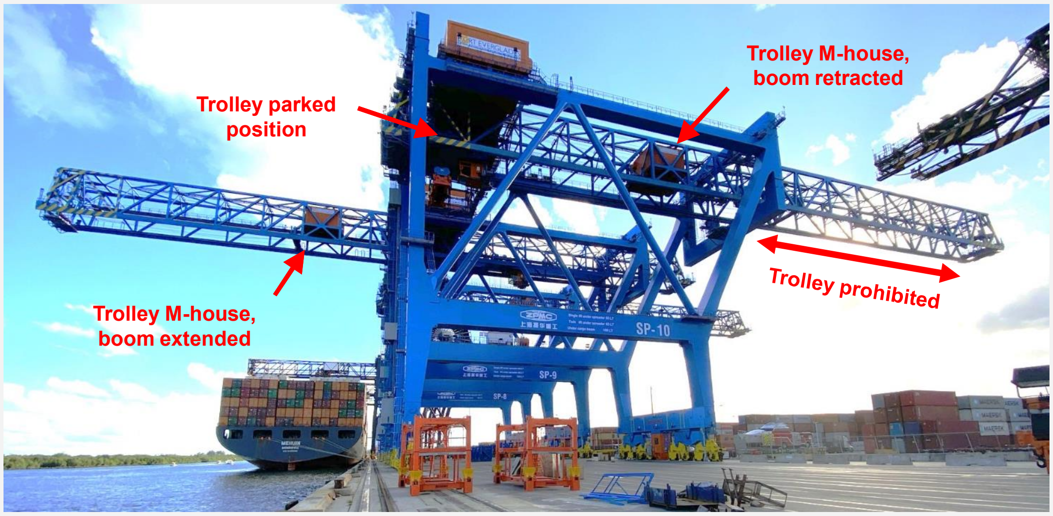
Having a shuttling boom introduces additional considerations for collision avoidance. The booms themselves have Sick sensors on the left and right of the booms for vessel collision avoidance during gantrying. There is also a sensor on the boom tip for collision avoidance during boom shuttling over the vessel.

The booms have the potential to touch during gantrying or boom retraction. The boom laser sensors are used as a redundant check for collision avoidance at this corner berth, with the primary system being the transponder-based positioning.

At the gantry level, there are anti-collision sensors at each gantry corner. This is an important feature not only for personnel protection, but also as a redundancy against gantry collision, which again is very undesirable for a low profile crane.

Trolley-Boom Synchronization

Electrical Considerations



Maintain parked position during boom shuttling
Trolley drive counteracts boom drive
Trolley prohibited behind O-frame
Failover drive sharing

27 of 29

This slide is about trolley-boom synchronization. While the boom is shuttling, the trolley drive reverses to keep the trolley in the same position relative to the crane frame.

The trolley machinery is inside of its own trolley machinery house. It is more efficient for maximizing lift height to move the trolley machinery out of the main machinery house, and it is packaged onto the boom itself.

Notice the crane in the foreground, where the trolley house is close to the landside support. Notice the image in the background when the boom is shuttled to the extended position. The trolley house has moved, but the trolley itself needs to stay in the same parked position while the boom is shuttling.

While the boom drive is operating, the trolley drive also needs to operate to compensate. This is unlike a conventional STS crane where the trolley and boom share a drive and operate one at a time. Low profile cranes need an extra drive compared with conventional cranes.

The trolley must stay in its parked position for two reasons. First, it keeps the trolley at its parked gate positions for accessibility. Second, the trolley is not permitted to pass behind the landside support area, for crane stability reasons. If the trolley did not compensate, then the boom shuttling would need to be interrupted to periodically reset the trolley position and avoid excessive travel to the landside or the waterside.

Recap and Q&A

28 of 29

We covered a lot of material today. We started with the purpose of low profile cranes, which are designed to have container operations in close proximity to airports. Then we showed how the shuttling boom design can offer similar lift height and outreach to a conventional crane, while saving nearly 200 feet of headroom.

The primary features of a low profile crane are a stiff truss boom, which is supported by upper and lower wheels, a saddle machinery house, and a sophisticated gantry system.

There are some fundamental engineering challenges to low profile cranes that need to be considered. The cranes are significantly heavier, imparting much heavier wheel loads and tie-down loads that need to be accounted for in the wharf design.

Also, the crane center of gravity, boom center of gravity, and wind center of pressure impose critical design considerations for lateral load conditions. The crane structure must be carefully evaluated, and the gantry machinery needs to be designed appropriately, including motors and braking systems that consider deceleration loads and skidding.

Finally, we talked about the nested headblock, the saddle design of the machinery house, and the separate trolley machinery house with a compensating trolley drive.

Thank You

This presentation will be available for download on our website:

www.Liftech.net

Quality Assurance Review:

Author: Steven Martinez

Editor: Linda Weber, Patrick McCarthy

Principal: Anna Dix