Anti-Collision Crane Distance Tracking System

by Laurence Amura

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Anti-Collision Crane Distance Tracking System

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Project submitted as part of the requirements for the BEng. (Hons) Electrical and Electronic engineering

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Student Declaration

I, Laurence Joel Amura declare that I am the sole author of this Project; that all references cited have been consulted; that I have conducted all work of which this is a record, and that the finished work lies within the prescribed word limits.

This work has not previously been accepted as part of any other degree submission.

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Form of Consent

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Abstract

Collision of high bay cranes and infrastructure still to this day poses a serious health and safety concern in industry. Although no fatalities have yet been reported in TATA Steel due to crane collisions, they have become a common occurrence with numerous "near misses" being reported. This is a problem which required addressing before serious injury or fatality occurred. Despite advances in technology, current crane safety systems are outdated and do not provide adequate indication and safety control.

This project aimed to research and develop a suitable anti-collision distance tracking system to be presented to management as potential solution to the problem in hand. It was required that the system provided a visual aid to the crane operator providing warning if the crane enters the pre-determined "warning" or "trip" zones as well as preventing collision. This was carried out with the use of a phase shift laser for distance measurement, a Siemens S7-1200 PLC for control and the development of a HMI user interface.

Although further work still remains to ensure the system is ready to be rolled out for installation on all TATA cranes, the system was implemented and proven to be a success with a satisfaction rating of all potential users at 87.5%, proven system accuracy within 2cm and a total build cost of £1,919.84.

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Chapter 1 – Report Introduction

1.1 Project Background

In a heavy industry such as steel making, cranes have always played a vital role in the transportation of materials due to the nature of the work required in industry. This commonly involves the moving of loads, which may be awkwardly shaped and on occasion extremely heavy. Without the use of vital equipment such as the crane many tasks that are commonly routine in industry would prove to be extremely time consuming, expensive and in certain cases, impossible. As a result the high bay crane is an essential resource in industry.

The Port Talbot Continuous Annealing and Processing Line (CAPL) consist of 3 main areas, entry, furnace and exit. The exit section of CAPL sees the final part of the steelmaking process where steel strip is tempered to its desired gauge, recoiled and finally stacked by the high bay crane ready for shipment to the customer.

Currently the high bay crane utilised for coil stacking has no form of position tracking or modern safety features to prevent collision and as a result has collided with plant causing severe damage. This is of course a severe health and safety issue which required addressing. See figure 1.



Figure 1 - Damage to infrastructure from crane collision in CAPL

As the high bay cranes in Port Talbot works are all manually controlled, usually by means of a crane driver in the crane cab, or less commonly by a hanging pendant, there is always room for human error allowing for the potential of crane to crane collisions on the same gantry or between the crane and other obstacles such as walls or infrastructure. This has been an ongoing problem in the steelworks for a number of years with many incidents occurring and no solution being provided.

It was therefore intended to deliver a reliable safety system solution to be presented to the CAPL engineering managers before securing funding for the implementation of such a system on the CAPL Exit crane and potentially all other cranes on the Port Talbot site requiring it.

1.2 Aims & Objectives

The aim of this report was to provide accurate distance tracking which will be programmed using either PIC or PLC control. The tracking will provide real time data allowing safety precautions to be installed to prevent collision of the crane into surrounding plant. It was also intended to design a HMI panel capable of being installed in the crane drivers cab to provide a visual display of the crane positioning in the bay along with audible alarms and warning lights when the crane is in 'Danger Zones'.

This project aims to research and provide an anti-collision distance tracking solution to the high bay crane in Port Talbot Continuous Annealing and Processing Line (CAPL). The system will involve selecting an adequate prebuilt sensor unit for the project and carrying out tests in a range of environments and parameters to ensure optimum accuracy and reliability. The results of these tests should determine the optimum operating conditions for the sensor. The laser system was then programmed using PLC control and incorporated into a fully operational indication unit equipped with a Human Machine Interface (HMI) for installation into the crane cab. The Unit will then provide real time feedback of crane positioning in the bay along with providing anti-collision protection between the crane and walls.

1.2.1 Mandatory Aims

The following aims have been deemed as mandatory for the success of this project.

- Research and provide a distance tracking solution for the Exit high bay crane on Port Talbot Continuous Annealing and Processing Line (CAPL)
- Provide detailed test results of the selected sensor to ensure it operates at its most reliable and accurate performance.
- Incorporate PLC control to allow for the utilisation of a HMI and crane driver indication panel.
- Carry out the installation of the system on a purpose built rig for presentation to CAPL engineering managers.

1.2.2 Design Objectives

This project aims to meet the following criteria:

- The system must be capable of integration into the present crane system to provide safety control.
- The system must incorporate PLC or PIC control
- The system must provide detailed distance feedback to provide anti-collision control within set parameters.
- A visual display panel must be incorporated to provide audible and visual display of crane positioning for the crane operator

Chapter 2 – Project Planning

Due to the nature of the project and criticalness of reduced downtime of the line (A single hour of unplanned downtime to the CAPL can incur costs of up to £12,000) an element of uncertainty arises when it comes to determining exact dates for work to be carried out.

It is impossible to predict exact dates for work to be carried due to the uncertainty of component delivery dates from Tata stores along with the unknown timescales associated with budget and funding allocation. This being said, rough estimates of dates can be provided however these will be liable for change. A full Gantt chart has been included (see figure 2 and appendix 5) outlining the key tasks of the project along with rough estimates of their timescales. It must also be stressed that these timescales are not an exact representation due to the uncertainty of line availability.

2.1 planning timescale

Task Name	Duration	Start	Finish	Predecessors
Research	**107 days**	**Fri 15/05/15**	**Mon 12/10/15**	
Current situation & effects of crane downtime	19 days	Fri 15/05/15	Wed 10/06/15	
Market research	20 days	Thu 11/06/15	Wed 08/07/15	2
Laser Theory	30 days	Thu 09/07/15	Wed 19/08/15	3
PLC theory	31 days	Thu 20/08/15	Thu 01/10/15	4
Communication protocol research	7 days	Fri 02/10/15	Mon 12/10/15	5
Hardware selection Process	**49 days**	**Tue 13/10/15**	**Fri 18/12/15**	
Laser selection	21 days	Tue 13/10/15	Tue 10/11/15	6
PLC selection	13 days	Wed 11/11/15	Fri 27/11/15	8
Other required hardware selection	15 days	Mon 30/11/15	Fri 18/12/15	9
Installation & Testing	**65 days**	**Mon 21/12/15**	**Fri 18/03/16**	
Purchase required hardware	10 days	Mon 21/12/15	Fri 01/01/16	10
Test laser to ensure correct for task	11 days	Mon 04/01/16	Mon 18/01/16	12
Install hardware	15 days	Tue 19/01/16	Mon 08/02/16	13
Write code	19 days	Tue 09/02/16	Fri 04/03/16	14
Functional Testing & tweaks	10 days	Mon 07/03/16	Fri 18/03/16	15
Analysis	**14 days**	**Mon 21/03/16**	**Thu 07/04/16**	
Analysis of laser performance	10 days	Mon 21/03/16	Fri 01/04/16	16
Possible enhancements	3 days	Mon 04/04/16	Wed 06/04/16	18
Final Report	**11 days**	**Thu 07/04/16**	**Thu 21/04/16**	
write final report	11 days	Thu 07/04/16	Thu 21/04/16	19

Figure 2 - Overview of Gantt chart tasks

Chapter 3 - Research & Review of Literature

3.1 Crane Background & Types

In order to determine how best to obtain a solution for this problem, it is first necessary to gain an understanding of what types of cranes are out there, as the solution must be adaptable, and also their operation. There are many various types of cranes available for various applications across the industrial sector. The various applications range from lightweight lifts with regards to workshop duties of a wall-mounted crane to colossal lifts undertaken by gantry and bridge cranes.

Overhead cranes are typically made up of two bridges equipped with parallel rails, connected by a trolley. This trolley supports a hoist for lifting capabilities. The trolley is able to move in a transverse motion along with the crane being able to move in a longitudinal motion. Overhead cranes are typically set up between fixed gantries mounted with rails to allow for the longitudinal motion of the crane (1). See figure 3.

3.1.2 Crane Motions

All overhead cranes have 3 degrees of travel available namely:

- Hoist (Vertical) motion
- Longitudinal motion
- Transverse motion

The hoisting motion is the directional movement on the vertical plane which raises or lowers the hook of the crane using a mounted electrical motor. The transverse motion allows for a trolley to move along secured rails attached to the bridge of the overhead crane. This motion allows perpendicular movement to allow for access to all areas within a bay area and is known as cross travel (2). The longitudinal motion is the directional movement along the horizontal plane the length of the bay. This motion is often referred to as the long travel motion and is the motion on which this project is centred (2). See figure 3

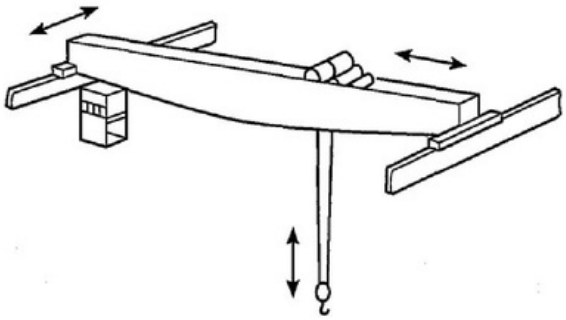


Figure 3 - Directional motions of an overhead bridge crane



Figure 4 - CAPL overhead bridge crane

3.2 Ultrasonic Distance Measurement

Ultrasonic sensors are commonly used for a vast variety of non-contact distance measuring. The typical operation of such a sensor is to transmit a short burst of ultrasonic sound toward a target, which in turn reflects the sound back to the sensor. The system then measures the time for the reflected echo to reach the sensor therefore determining the distance to the target using the speed of sound medium (3). See Figure 5

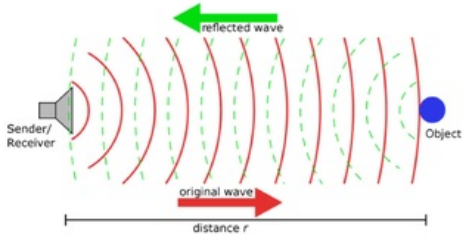


Figure 5- Ultrasonic ranging technique (4)

Ultrasonic sound is a vibration at a frequency >20kHz, above the range of human hearing Most ultrasonic sensors will use a transducer which will transmit and receive the reflected echo, typically at a frequency of between 40-250kHz (3). The principle for this method is to measure the time of flight (TOF) of the ultrasonic burst, i.e. the time lapse between the firing up of the transducer and the detection of the echo. The distance to the target, x, (reflective surface) is gained through the expression:

$$x = c.\frac{t}{2}$$

Equation 1

Where c is the propagation velocity of the ultrasonic burst, and t is the TOF estimate.
The speed at which the sound travels depends greatly on the medium it is passing through with the physical properties of the speed of sound varying with the conditions in the environment such as temperature, humidity and gas (5).

3.2.1 Speed of sound

As previously mentioned, the speed of sound varies greatly dependant on the medium it is passing through which is altered depending on the environment. It is assumed that the speed of sounds is proportional to the stiffness of the medium and its density (6).

The speed of sound in air is a function of both the composition and temperature of the air at that time with the speed increasing linearly with temperature. See figure 6.

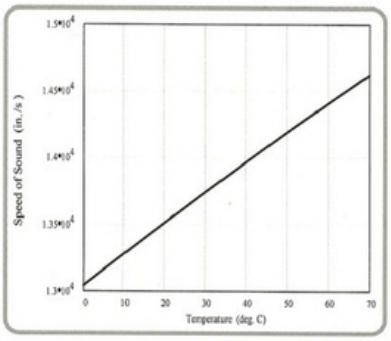


Figure 6 - Speed of sound as a function of temperature (3)

The speed of sound in air can be calculated as a function of temperature by the relationship:

$$c(T) = 13{,}044\sqrt{1 + \frac{T}{273}}$$

Equation 2

Where:

c(T) = speed of sound is air

T = temperature of air in ^{0}C

The speed of sound also varies dependant of the gaseous medium in the air and can be altered dependant on the chemical composition and temperature. A speed of sound for various gasses at 0oC can be seen in table 1 (7).

Table 1 - Speed of sound for various gasses

Speed of sound for various Gasses	
Gas	**Speed in./s at 10oC**
Air	13,044
Ammonia	16,332
Argon	11,886
Carbon Dioxide	10,152
Carbon Disulphide	7,272
Carbon monoxide	13,272
Chlorine	8,088
Ethylene	12,360
Helium	38,184
Hydrogen	49,980
Illuminating gas	19,308
Methane	17,004
Neon	17,124
Nitric oxide	12,792
Nitrogen	13,152
Nitrous oxide	10,308
Oxygen	12,492
Steam (100oC)	15,876

3.2.2 Wavelength of sound as function of sounds speed and frequency

The wavelength of sound will change as a function of frequency and sound speed as seen by the expression:

$$\lambda = c/f$$

Equation 3 (3)

Where:

λ = wavelength

c = speed of sound

f = frequency

3.2.3 Attenuation of sound as a function of humidity and frequency

The amplitude of sound pressure is significantly reduced due to friction losses in the medium it is passing through the further it travels. This can greatly affect the range of the sensor if not accounted for. As the attenuation of sound increases with frequency in air, at any given frequency the attenuation will also vary as a function of humidity. As stated in the Part 1 of 'choosing an ultrasonic sensor for proximity or distance measurement' published by Massa The maximum attenuation however varies at different frequencies for example, at 125kHz the maximum attenuation occurs at 100% RH, whereas at 40kHz, the maximum attenuation occurs at 50% RH (3). It can be clearly determined therefore that humidity in the environment can play as significant role in the accuracy of the ultrasonic sensor.

3.2.4 Sound Reflection

As previously mentioned in order to measure the distance of a transmitted sound signal, it needs to be reflected. If the sound pulse is reflected from a large flat surface, then the whole beam is reflected.

3.2.4.1 Surface

The ideal surface for ultrasound reflection is hard and smooth as this will reflect a greater amount of the signal than a soft rough surface (6). Hence a weak echo can be the result of either a small, soft or excessively rough object which can reduce the operating distance and accuracy of the sensor. This is confirmed in a report by Oswald Leroy on the "diffusion of ultrasonic wave by a simple rough surface", where he states from "from light-diffraction by ultrasound, for certain incident angles most energy is diffracted in one order". He proceeds to entitle these angles 'Bragg-angles' stating that analogous results appear from the

diffraction of ultrasound against rough surfaces. The relation between the incident angle Θ_n and the diffraction angles Θ_l
(Bragg-angle) Is given as:

$$sin\emptyset_n - sin\emptyset_t = (n-l)\lambda/\mathrm{A}$$

Equation 4

It can be deduced that those incident angles for which the diffracted sound returns in the incident direction is given by:

$$sin\emptyset_n = (n-k)\lambda/2\mathrm{A}$$

Equation 5

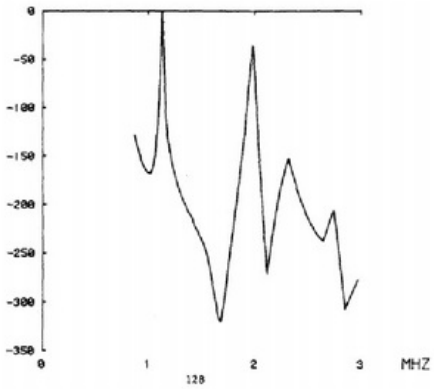


Figure 7 - Reflected intensity against frequency

3.2.4.2 Distance

The less distance between the ultrasonic sensors to the reflecting object, the stronger the returning echo (6). This is due to the amplitude of sound pressure is significantly reduced due to friction losses in the medium it is passing through the further it travels as previously stated. Therefore as distance increases between object and sensor, the object requires improved reflective characteristics in order to ensure a sufficient echo is received back to the sensor. According to Rockwell Engineering the target size and material determine the maximum distance at which the sensor can operate with the material of the reflective surface playing a role in reflectivity as mentioned in the previous section. A representation of maximum distance between sensor to target can be seen in figure 8.

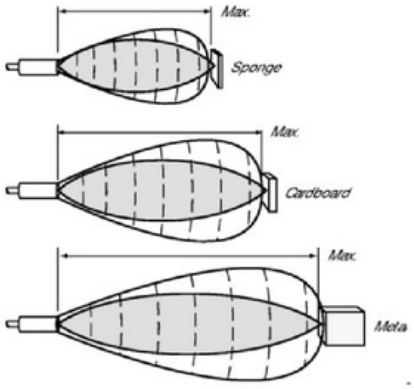


Figure 8- Sensing range with maximum sensitivity (8)

Ultrasonic sensors do have a minimum distance for operation, as the small area (dependant on sensor) near the face of the sensor is unusable. This is normally due to the emitted signal striking the target and returning to the sensor receiver before the transmission has been completed (8).

3.2.4.3 Size

The size of the reflective surface plays a role in the strength of the signal echo based purely on the fact that a larger surface area reflects more than a of a small surface area due to less loss of signal.

3.2.4.4 Angle

The inclination of an objects surface in relation to the sensor affects how well the object reflects the ultrasonic to the sensor (6). The angle at which a target will be detected is known as the 'beam angle'. If a target moves closer to the sensor or if the transmitting signal is increased, then the effective beam angle will increase (3). At the maximum detection range of the sensor, the echo is barely being received by the sensor and is in direct alignment with the reflective surface. By rotating the target slightly off the beams acoustic axis at this range, the amplitude of the echo will lower below the sensors sensing threshold and become undetectable. Under these conditions the effective beam angle will therefore be 0°C.

As a target moves close to the sensor on the other hand, the echo level increases drastically. According to a report by Massa Products corp, for a sensor operating at 100 kHz and using a large flat surface as a reflecting target, the echo level can increase by up to 60dB as the

target moves between distances of 10ft to 1/2ft. This means that any angle at 1/2ft the sensor beam has not reduced by more than 60dB, the flat target produces an echo larger than that of the target on an axis at a distance of 10ft (3).It can therefore be concluded that the effective beam angle changes depending on the distance of the target and the strength of the reflection from the target. See figure 9 for some reflector angle cases:

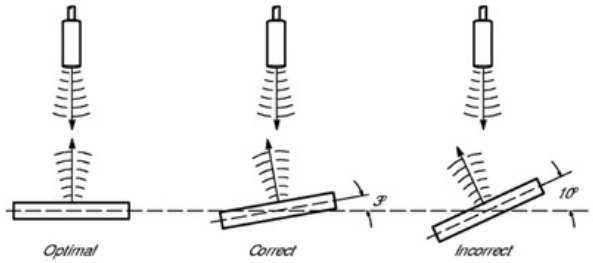


Figure 9 - Alignment of flat target (8)

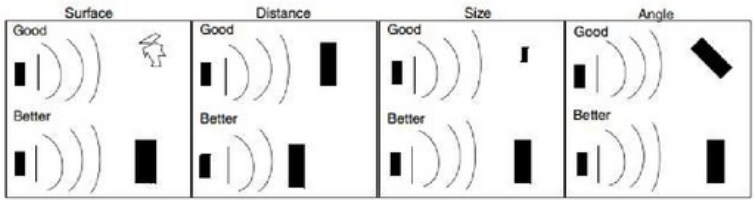


Figure 10 - sound reflection cases

3.2.4.5 Noise

The level of ultrasonic background noise is reduced as frequency increases. This is due to less noise at the higher frequencies being produced in the environment with whatever noise that is produced being mainly attenuated as it travels through the air (3).

3.2.5 Ultrasonic Advantages

1. Ultrasonic response is not dependent on surface colour or optical reflectivity. For example, the sensing echo strength of a clear glass pane, brown pottery plate, white plastic plate or shiny chrome plate is the same (8).
2. Due to the relatively low switching hysteresis for on/off ultrasonic sensors, it is possible for the sensor to ignore immediate background objects even at long sensing distances (8).

3. The response of an analog ultrasonic distance sensor is linear with distance. This makes them perfect for interfacing with displays such as LEDs to give a visual indication of the target distance (8).

3.2.6 Ultrasonic Disadvantages

1. Ultrasonic sensors must view the target at the effective beam angle in order to receive an echo. Targets not placed perpendicularly can cause sensing issues. They also require a minimum target surface area which is specified by each sensor.
2. Whilst offering good immunity to noise, ultrasonic sensors still have the potential to falsely respond to certain loud noises such as the sound produced by pressure relief valves (8).
3. Proximity ultrasonic sensors require the transducer to stop 'ringing' after it has transmitted a sound pulse before it can receive the returned echo. This results in them having a typically slower response time than other technologies at about 0.1s. Transmitted beam style ultrasonic sensors are far quicker with response times of 0.002s to 0.003s (8).
4. All ultrasonic sensors have a minimum sensing distance
5. Environment conditions have an effect on ultrasonic response, as discussed previously temperature, pressure and humidity can affect the response of the sensor (8).
6. Low density targets such as foam and cloth can absorb the sound energy reducing their reflectivity and hence making them difficult to sense at longer range.
7. As smoothness of a surface increases, the more efficiently it can be detected however the sensing angle to a smooth surface is generally more critical than a rough surface (8).

3.3 Photoelectric sensors

Photoelectric sensors are readily present in everyday life helping the safe control of a vast array of processes such as garage doors, elevators, and steel coil detection in a stock bay. The photoelectric sensor detects a change in light intensity, typically the detection or non-detection of the sensors emitted light source making them a rugged and relatively simple method of detection. The photoelectric sensor is made up of a light source (LED), a receiver (phototransistor), a signal converter and an amplifier. The incoming light to the receiver is then analysed and verified resulting in the sensor triggering an output (9).

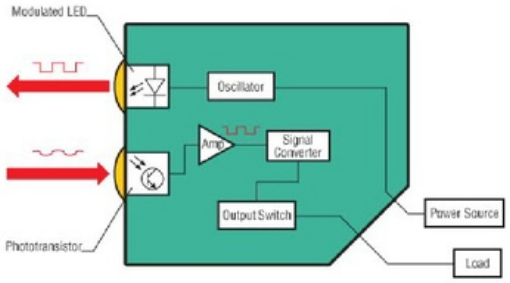


Figure 11 - operation of a photoelectric sensor (9)

3.3.1 Diffused Mode

Diffused mode sensing or proximity sensing utilises a transmitter and receiver in the same housing. A light source from the transmitter is reflected from a target at arbitrary angles with some of the light being returned to the receiver. As large amounts of the transmitted energy is lost due to the targets angle and reflectivity, this mode has shorter sensing ranges than what is achievable with retro reflective mode (9).

3.3.2 Diffused Convergent Beam Mode

Convergent beam mode is the most efficient method of diffused sensing. In this mode the transmitter lens is focussed to a precise point in front of the sensor along with the receiver lens being focussed to the same. This results in a fixed sensing range. The sensor can then detect objects in this focal point plus or minus the distance known as the “sensing window”. This means that any objects outside the window are ignored. See figure 12 (9).

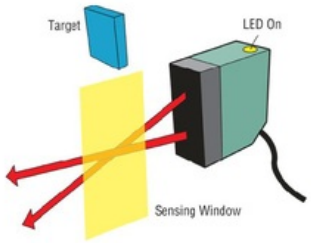


Figure 12 - Diffused convergent beam sensing window (9)

3.3.3 Retro-reflective mode

Retro-reflective mode is the second primary mode of photoelectric sensors (9).The transmitter and receiver are housed in the same unit with the transmitted beam requiring a reflective target to reflect the light source back to the receiver. The target is then detected when this light beam is blocked. Retro reflective type photocells allow longer sensing distances than other types due to the increased reflectivity efficiency of the reflector as opposed to other surfaces. Target colours or finishes has no effect on the sensing range when using retro-reflective type as opposed to diffused type and others.

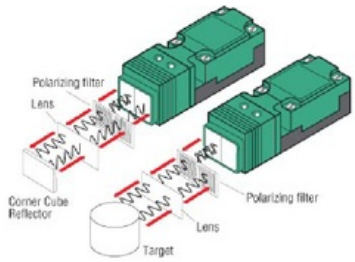


Figure 13 - operation of a retroreflective photocell (9)

Photoelectric sensors offer many advantages over other technologies such as a large sensing range surpassing many alternatives, small size for sensing range, variety of housings and their relatively low cost.

Although these may seem like the perfect option for a crane safety system there are a few issues which must be mentioned. Firstly, the sensor unit does not offer an accurate analog signal which can be used for precise distance measurement and secondly, the strength and reliability of the reflected signal depends greatly on the reflectivity of the surface. This can pose an issue in harsh or dirty environments which may cause staining of the reflector and

as a result, reduce the reliability of the signal. An example of different object reflectivity when the sensor is in diffused mode (no reflector

3.4 Laser Distance Measurement

Laser rangefinders are widely used in the fields of spaceflight, robot vision, mapping, manufacturing and safety systems for their merits of being non-contact, highly precise and relatively low cost. A laser rangefinder can be utilised in various ways in order to measure distances without any physical contact and offer and are widely recognised as one of the most accurate forms of distance measurement offering sensitive and precise measurements even for extremely fast recordings (10).

There are a number of techniques used for laser distance measurement including time of flight (TOF), triangulation, frequency modulation continuous wave (FMCW) and phase shift which will be discussed.

3.4.1 Pulsed Time of Flight Laser Rangefinder (TOF)

Time of flight (TOF) method was originally used in the military and for surveying applications but has since become more commonly used in industrial applications such as for the position of ships and cranes along with the measuring of stored liquids or solid materials (11) (12). It is therefore one of the most widely used techniques for long distance measurement when the range is from the scale of several hundred metres to tens of kilometres. Continuous wave lasers are generally reserved for triangulation, phase shift and FMCW techniques up to one hundred metres. As these lasers use continuous wave (CW), unlike a pulse TOF rangefinder, their distance is limited to less than 1km due to the fact that the range finding system becomes more complicated as the repetition rate of the transmitter power increases. Contrastingly, when the repetition rate is decreased, the laser struggles to detect high speed targets. There is therefore usually a trade-off between maximum distances or the repetition rate and system complexity (10).

3.4.1.1 Principles of a TOF rangefinder

TOF (or pulse measurement) is based on measuring the time of flight of a laser pulse from the measurement device to the target and then back to the receiver. If using light as the energy source (such as laser) the relevant parameter in range counting is the speed of light (approximately c = 30cm/ns) (11). It is therefore measuring the round trip of a pulse echo

resulting from the reflective capacity of the target object (see figure 14). Distance can therefore be determined by multiplying the speed of light by the time the light pulse takes to travel the round distance. Since the velocity of light is known, the time measurement can be converted into a two way measurement as expressed by the equation (13)

$$2R = c\,t_r$$

Equation 6

Where c = speed of light, t_r = round trip transmit time.

In the case of figure 8, the measured time must be halved as it is representative of travelling twice the required measured distance.

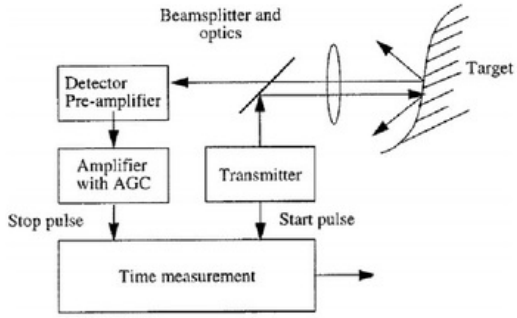


Figure 14 - Block diagram of TOF laser rangefinder

A timing discriminator is used to determine t_r by measuring a specific point of the pulse, the "leading edge". This is the rising edge of the initial pulse and is known as "leading edge detection" as shown in figure 15 (13).

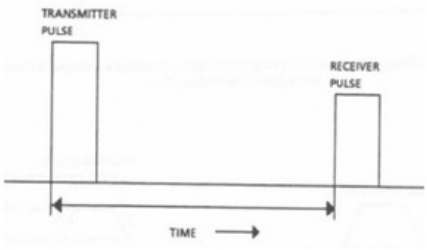


Figure 15 - Pulse range measurement by leading edge detection (13)

A pulse from a laser transmitter in reality does not have an instantaneous rise time and as a result the leading edge detection needs to be more accurately defined at a set voltage. This is accomplished with a threshold trigger in the timing discriminator and can be seen in figure 16

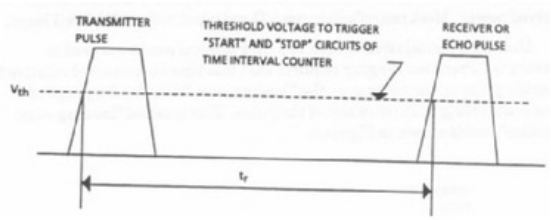


Figure 16 - Leading edge detection using threshold trigger (13)

As a single pulse is adequate for providing the means to determine the distance with high accuracy one advantage of the TOF system is that both the transmitted and returned signal follows essentially the same path from the transmitter to the object and back to the receiver (11). By using shorter laser pulses and a wide bandwidth, many parameters can be improved such as reducing walk error, increasing single shot precision and also providing the possibility to distinguish between two successive pulses (12). However a report into low-noise high accuracy TOF laser rangefinders published in the American Journal of Applied sciences states that by reducing the pulse width of a signal, the output power of the laser can be increased to several MW having the resultant effect of reducing the signal to noise ratio. It is therefore a matter of assessing the application in order to determine what factors are more important or necessary.

3.4.1.2 Constructions of a TOF Rangefinder

As previously mentioned a pulsed TOF rangefinder consists of a laser transmitter which will emit pulses with a duration of 5 to 50ns, a receiver which incorporates an avalanche photodiode (APD), amplifiers, automatic gain control (AGC) and timing discriminators (11). As seen in figure 14, the light pulse travels a distance of 2r; the receiving power is generally small. The relation between the received power at the sensor receiver Pi and the distance r is defined as;

$$Pi = \frac{\tau . A . \exp(-2\alpha r)}{\pi r^2} . \rho . Popt$$

Equation 7

$$\tau = \tau c . \tau opt$$

Equation 8

where t is the transmission coefficient, c is the absorption coefficient and p the reflection coefficient of the target where p =1 for a perfect reflector such as a mirror and is equal to zero for a non-reflective black surface. The laser output power is defined as P_{opt} and A is the sensor receiver optic area.

The emitted pulse of light or start pulse will trigger the time interval unit allowing it to begin counting until the stop signal is received. The reflected light pulse or stop pulse will then travel the distance of 2r, from the emitter to the target and then return to the sensor receivers APD which has high responsivity and a short rise time. The counter is stopped when the APD output photocurrent is converted to a voltage signal which is then amplified. The distance between transmitter and target in terms of clock pulse frequency (fclk) is expressed as;

$$r = \frac{cN}{2f\ clk}$$

Equation 9

where N is the digit count between the start and stop signal and c is the speed of light. The number of clock pulses The time interval recorded is therefore proportional to the target distance.

3.4.1.3 Error Sources and Noise

The primary source of inaccuracy in laser range finding is noise generated by timing jitter, walk, nonlinearity and drift (12). This can involve changes in the pulse shape, amplitude and changes in the delay of electrical or optical signals. If more than one error source is present but all the sources have an effect on the same error independently, then the total root-mean-square (rms) error is determined by summing the squares of the individual error components.

Typical noise sources could include one shot noise created by electronics, background radiation induced current and signal current. Timing jitter determines the precision of the range measurement and is proportional to noise amplitude, or rms, and inversely

proportional to the slope of the timing pulse at that precise moment of timing (du/dt) (11). As an example of this, a critical review of laser ranging techniques published in July 2000 states that a single shot resolution of 1cm can be achieved with a good signal (SNR = 100), using he 100MHz bandwidth of the receiver. However as the distance increases and the pulse amplitude decreases proportionally to the square of the distance, precision begins to deteriorate (12). Walk error refers to the error in the distance measurement result which is dependent on distance, reflection and the coefficient measurement angle (12). This is an important factor in a TOF rangefinder as this can have a big impact on the power of the received pulses. Pulse amplitude and waveform variations create this timing error. This walk and jitter in the edge timing can be seen in figure 17

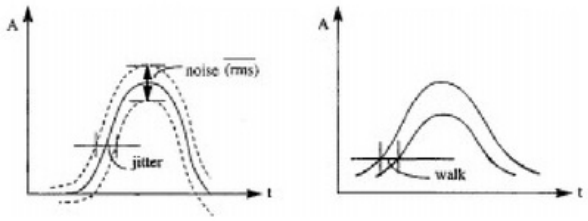


Figure 17 - Timing walk and jitter

3.4.1.4 Summary of Pulsed TOF rangefinders

1. Generally reserved for larger distances (e.g. from 100m to hundreds of kilometres)
2. Beam quality is crucial for accurate long range measurement (i.e. small beam divergence and high energy pulses)
3. Recognised as one of the most accurate forms of long distance measurement

3.4.2 Phase-shift laser rangefinders

The principles of a laser phase shift rangefinder are discussed in the following sections. The limitation of the method such as high level of photoelectric signal, intermediate frequency drift and electrical crosstalk are also discussed.

3.4.2.1 Principles of a laser phase shift rangefinder

A laser phase shift rangefinder is based on amplitude sine wave modulation of laser intensity and then conversion of the flight time as a result of propagation phase shift. A laser beam with sinusoidal modulated optical power is sent to a target with some of that reflected light being collected by a photodiode with the phase of the modulated power is being compared to that of the emitted laser phase angle (see figure 18). The phase shift of the laser is directly proportional to the TOF, the *term time-of-flight* method generally refers to the method discussed previously where the time delay is measured more accurately (10).

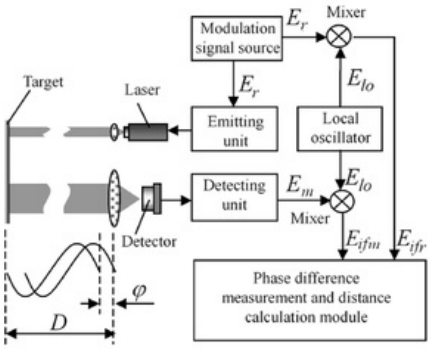


Figure 18 - Block diagram of phase shift laser range finder (14)

The phase shift is represented by:

$$\Delta\emptyset = \omega_l t_d = 2\pi f_l \frac{2d}{c}$$

Equation 10 (15)

The distance D, can be obtained by measuring the phase shift and is expressed as:

$$D = \frac{c}{2f} \cdot \frac{\varphi}{2\pi}$$

Equation 11 (14)

Where c is the velocity of light, f is the modulation frequency and Φ is the phase shift angle between the measurement signal and reference signal.

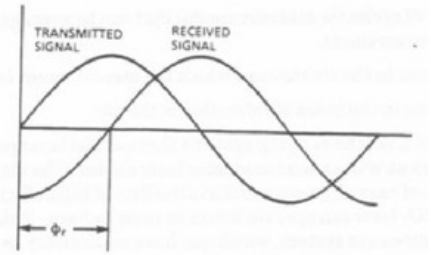


Figure 19 - Phase comparison measurement (16)

Equation 12 shows that the phase shift between the received and transmitted signal must be measured accurately to obtain an accurate distance measurement (14). It is important to have a good resolution of the phase shift measurement which can be achieved using what is known as the heterodyne technique. Using this technique the phase shift is written as:

$$\Delta\varphi = 2\pi T_x / T_{IF}$$

Equation 12

where T_{IF} is the period of intemediate frequency signal and Tx is the time (17)

3.4.2.2 Received Signal Strength

If the target area is the same size as the area illuminated by the transmitter, the received signal power P_R can be expressed as:

$$P_R = T_T T_R \frac{Pd}{\pi} P_0 Cos\theta \frac{A_R}{D^2}$$

Equation 13

Where P_o is the power output, T_t is the collection and transmission efficiency, T_r the transmission of the receiver, P_d the reflection coefficient of the target, Φ the laser beam incident angle and A_r the area of the receiver lens (11).

3.4.2.3 Error Limitations Analysis of Phase Shift Rangefinders

The following section discuses some error limitations of phase shift rangefinders.

3.4.2.3.1 High Levels on the rf channel

It is possible for power ratio of P_r / P_o to vary with a factor greater than 1000 if the distance, D varies from 1 to 10m for example. Therefore when the photoelectric signal varies by a factor of 1000, the phase shift error introduced must be less than 0.1 degrees for an error distance measurement of 2.5mm (11). However if there is a large amplitude of the useful signal then phase shift errors are introduced by clipping and distortion. This can be avoided by either defocussing the photodiode so that it receives less light when measuring small distances or by increasing the feedback of the mixer to avoid clipping and distortion.

3.4.2.3.2 Intermediate frequency drift

When a low power laser diode is being utilised, narrow bandwidth amplification can help improve the signal resolution. If there is white noise present at the input, the output of a passband filter presents a noise equivalent bandwidth given by:

$$B_n = (\pi/2)\Delta f_{rf}$$

Equation 14

Therefore the rms noise of the signal is directly proportional the square root of the bandwidthΔf_{if}. Therefore there is no error f the two frequency filters are identical on reference and signal channel. If one bandwidth is too narrow then then this can present noise in the system. To ensure the resolution is kept at its highest, the value of the intermediate frequency must be kept at a constant using a phase locked loop technique (11).

3.4.2.3.3 Influence of crosstalk

Crosstalk exists between the transmitter and the receiver producing an error. If the photoelectric signal and the modulation current share the same frequency, then the synchronous leakage arising from the modulation current source is overlaid on the working photoelectric signal (11). As this crosstalk cannot be completely removed using shielding techniques, other methods can be utilised to try to overcome this issue. Firstly, to reduce the effects of field leakage, the gain switch of the laser diode is utilised as a light comb generator, and an APD selecting the second harmonic of the photoelectric signal. Secondly, a

method based on the use of pockets cell has been known to be utilised although its implementation is difficult (11).

3.4.2.4 Summary of phase shift laser rangefinders

1. Utilising phase shift method for distance measurement is a good option if a resolution of a few millimetres in 1 to 20m ranges is required with non-cooperative targets (although distance can range further than this).

2. As the photoelectric current utilises a sine wave, a large area photodiode can be utilised to achieve a wide angle of the field of view.

3.4.3 FMCW Optical Radar

Optical distance measurement using frequency modulated-continuous wave (FMCW) technique is used in many applications such as non-contact surface profiling, fibre optic sensing positioning and reflectometry (11). Due to recent advances in FMCW technology there is now a great interest in this method of range finding due to their large dynamic range and high resolution at short sensing ranges.

3.4.3.1 Principle of FMCW rangefinders

The setup of an FMCW radar system can be seen in figure 20. The frequency of the modulated laser diode shifts the optical power by Δf, which is utilised as a probing signal as seen in figure 21

The periodic and linear frequency chirp is carried out by utilising a saw tooth boas current to the modulator section on the wavelength-tuneable diode. The transmitted laser output then passes an optical isolator to prevent any deterioration of laser frequency and is then transmitted simultaneously to the object and the reference mirror. The reflected signals are then superimposed in a square law detector diode (11). Finally the intermediate frequency f_{if} of the reflected signals is measured by a frequency counter. This can be seen in figure 20

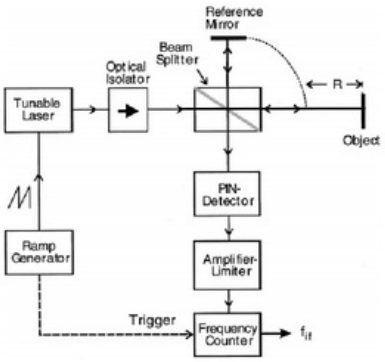


Figure 20 - Set up of FMCW optical radar system using tuneable laser diode as light source (11)

It is noteworthy that due to the square law mixing process, the amplitude of the detector output at f_{if} is directly proportional to the amplitudes (rather than the powers) of both the signal and the reference. Therefore the range of the FMCW technique is twice as large as that of the pulse radar technique where the electrical signal is proportional to the object signal power (11).

The difference in range between a target and reference mirror, R, which is what is required to be determined, is proportional to f_{ive} as can be seen in figure 20 as the round trip time of the signal is given by:

$$T = 2\,R/c$$

Equation 15

Where c is light velocity, then the intermediate frequency is given by the equation:

$$f_{if} = \frac{\Delta f \tau}{t_m} = 2\Delta f R/c t_m$$

Equation 16

Where t_m is the ramp period and normally 0.1 to 1ms. Therefore the distance measurement is carried out in the kilohertz regime by an electric frequency measurement as opposed to the delay time being measured directly as with the pulsed TOF rangefinders. Therefore, the FMCW technique can measure the delay time of the signal in the pico second range

according to mm distances by carrying out frequency measurement in the kilohertz regime (11).

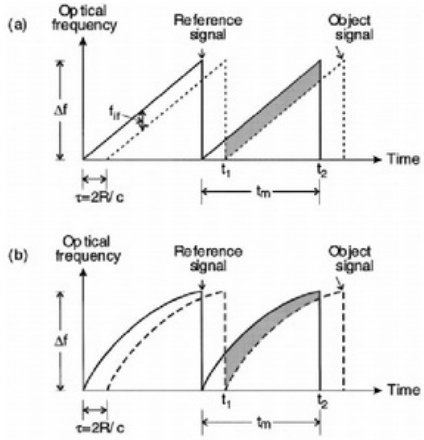


Figure 21 - Instantaneous optical frequencies vs time of object & reference mirror signal (a) linear optical frequency ramp (b) nonlinear optical frequency ramp (11)

3.4.3.2 Limitations of FMCW

One drawback of this method is that the FMCW laser diode is limited by the coherence length of the laser diode, usually in the order of several tens of metres as a consequence of laser diode phase noise. Laser diodes that have narrow linewidths within the frequency sweep range are generally more suited to measurement of longer distances. However in recent years, it has been documented that this limitation can be overcome by utilising a frequency shifted feedback laser which has supposedly reported measurements up to 18km. (18)

Another and most important limitation of the FMCW technique is that the accuracy of the measurement is dependent on the phase noise present in the laser diode (19). Low frequency phase noise occurring in the f_{if} frequency range can plays a part in limiting this method.

3.4.3.3 Summary of FMCW technique

1. Due to advances in technology in recent years, the FMCW technique is a good option for range finding due to its large dynamic range and high resolution at short sensing distances

2. If the electrical signal is proportional to the object signal power then the range of the FMCW is twice that of the pulsed TOF method.

3.4.4 Comparison of TOF, Phase Shift and FMCW

As discussed in the previous sections it can be clearly seen that each method possesses its own distinct characteristics. A number of factors have to be considered when choosing the correct method for the desired application such as price, accuracy and range of each method just to name a few. An experiment published in the quarterly journal of technology and education in 2006 produced the following result comparison table indicating some of the performances of each of these techniques. See figure 15

Range Finding Methods	TOF	FMCW	Phase-Shift
Laser Source	Nd:YAG, Q-Switch	Semiconductor	Semiconductor
Power	1.5MW	3mW	10mW
Wavelength	1064nm	650nm	1100nm
Detector	APD	APD	APD
Range	300-20km	2-30m	2-400m
Sampling Rate	1-20Hz	4kHz	52Hz
Minimum Detectable Power	12.7nW	200nW	23pW
Accuracy	5m	36mm	21mm
Oscillator Frequency	30MHz	4-60MHz	1MHz
Driving Power	Three Phase	Single Phase	Single Phase
Laser Driving Waveform	Pulse	Ramp	Sinusoidal
Cost	Expensive	Low Cost	Low Cost
Structural Complexity	Simple	Complex	Complex
Distance Measuring Equation	$d=\frac{CN}{2f_{ck}}$	$d=\frac{F_sCT_r}{4\Delta f}$	$d=\frac{C}{4f}$

Figure 22- comparison of TOF, FMCW and Phase Shift laser range finding methods (15)

3.4.5 Laser Target Considerations

As previously discussed, the maximum range of a laser rangefinder represents the distance between the target and the sensor at which detection is possible. In an ideal situation the detection target is considered from the detections of all point targets as can be seen in figure 23 (20).

3.4.5.1 Point Targets

A point target consists of the target being smaller than the area of the transmitted beam (see figure 23). The scattering area or RCS is defined as

$$\theta = 4\pi p_t A_t / \Omega$$

Equation 17

Where p_t is the target reflectivity, A_t is the target surface area and Ω is the scattering steradian angle of the target. The scattering area (RCS) is assumed to be constant due to the surface area of the target being constant. Therefore the receiving power of the laser beam has no dependency on the target scattering area. From the range equation the receiving power can be represented by:

$$p_t = \frac{1}{r^4}$$

Equation 18

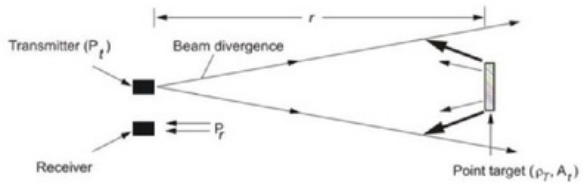


Figure 23 - Schematic of the detection of point target (20)

3.4.5.2 Extended Targets

An extended target consists of the surface area of the target being larger than the incident laser beam area. This results in the entire laser beam being involved in the reflection from the target surface as can be seen in figure 24. The scattering area of the target now has a direct effect on the receiving power of the signal. From the range equation, it can be represented as the receiving power:

$$P_r \propto \frac{1}{r^2}$$

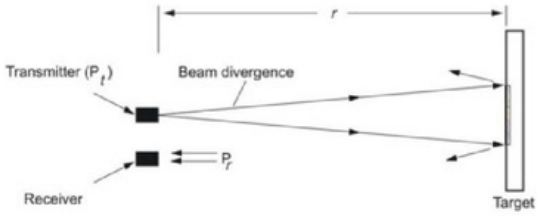


Figure 24 - Schematic of extended target detection (20)

3.4.5.3 Reflectivity of targets

The reflectivity of a target depends on the surface properties of that target. For example, a mirror target would have a specular reflection whereas diffuse type targets have a larger scattering reflectivity. These will be discussed.

3.4.5.3.1 Mirror type targets

In the case of a mirror type target, the incident wave is redirected towards the sensor as can be seen in figure 25. In theory, a typical mirror target follows the law of reflection where the angle of reflection is equal to the angle of incidence (20).

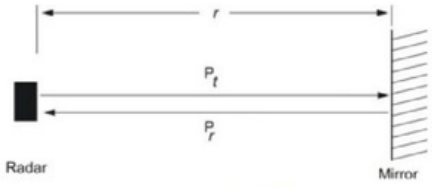


Figure 25 - Reflectivity of mirror type target (specular reflection) (20)

3.4.5.3.2 Lambertian type targets (Diffuse)

A purely diffuse target has a larger scattering field as a result of the targets granular surface properties. If a target were to have a completely non-specular surface, then the reflected light will spread over a hemisphere as seen in figure 26. As the light is spread over as a hemisphere, the scattering steradian angle is equal to 2π (20).

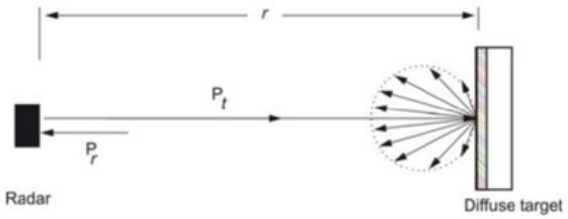


Figure 26 - Reflectivity of a diffuse target (large scattering reflection) (20)

3.4.6 *Advantages of laser rangefinders*

Laser rangefinders pose a number of advantages over other methods of range finding, some of these include (21):

- Potential to have very high accuracy up to 1mm for phase angle range finders
- Highly reliable measurements in harsh our difficult terrain such as obstacles being present.
- Extremely long measuring range capability should it be required. (300-20km for TOF pulsed rangefinders.
- Visible laser spot for easy alignment and visual indication
- High efficiency measurements for angled targets.

3.4.7 *Disadvantages of laser rangefinders*

As with any technology, there are also some drawbacks to utilising laser as a means of range finding, some of these are listed below:

- Can prove to be considerably sensitive in direct sunlight as reflected signals can be dispersed resulting in insufficient power on the return pulse at the receiver preventing accurate distance measurement being carried out.
- Transparent objects can prove to be an issue as many laser types will not sense them; specific lasers must be utilised (21).
- Laser measurement systems can be very complex as discussed in previous sections resulting in a relatively high cost in comparison to other technologies such as ultrasonic sensors.

3.5 Market Research

In order to gain an understanding of what systems are already available it was required to conduct a market research review. Some products along with their features are listed in the following section.

KAD-300

The KAD-300 crane collision avoidance system utilises an LED based retro reflective type sensor to provide protection against collisions of overhead cranes. A typical application for this unit would be mounting it on the bridge of the crane along with a reflective target on the opposing end wall, or bridge crane at a total distance of 100 feet. The unit offers 3 separate outputs to initiate slow down and stop commands along with a fault output which energises in the event of emitter/receiver failure. Features include: (22)

- LED based Retro reflective type sensor
- relay output (No scalable signal)
- 100-240V AC power supply
- Sensing range of 1 to 30m
- Requires retro reflective target 2ft x 2ft
- Operating conditions -10 to +55oC, relative humidity less than 85%
- +/- 2.5°Directional angle



Figure 27 - KAD 300 (22)

Catron LCAS

The LCAS utilises class 1 laser light retroreflective technology providing an alarm output and stop functions at pre-set distances with a total range of 50m. The alarm activates if the unit detects a target within the set warning distance. Features include (23):

- Retroreflective class 1 laser
- 0.3m to 50m range
- Selectable alarm and stop output settings
- Internal by-pass switch to override
- LED status lights
- 100-240V AC supply
- Continuous circuit fault monitoring



Figure 28 - LCAS system (23)

LaserGuard 2

The laserguard 2 utilises self-monitoring lasers to check the cranes position and utilises flexible multi distance detection for crane to crane or crane to wall protection. Features include (24):

- 8 inch to 150ft detection range
- Laser technology
- 85-264V ac supply
- 3 individual contact closures at selectable ranges
- Visible led power light requires 2x2ft reflector
- Price: $2,295



Figure 29 - laser guard 2 system (24)

Gigasense

The Gigasense system is a fail-safe crane anti-collision system which utilises microwave technology between a transmitter and receiver on opposing each other. Using the Doppler technique. The distance, speed and movement of the crane can be controlled via the relay box with 3 outputs. Features include (25):

- Microwave sensing technology
- 0-25m working distance



Figure 30 - gigasense system (25)

• 0.1 to 5m/s range • -25°C to +70°C • Relay outputs for warning stop and function control. • 230V AC supply	

3.5.1 Comparison Table

Table 2 - Comparison of market research

Features	KAD-300	LCAS	LaserGuard	Gigasense
Sensing technology	LED Retroreflective	Laser Retroreflective	Laser Retroreflective	Microwave
Working Distance	1-30m	0.3-50m	0.2-46m	0-25m
Supply voltage	100-240V	100-240V	85-264V	230V
Outputs	3	3	3	3
Analog output	No	No	No	No
Visual Display	No	No	No	No
Visual Indication (LED)	Yes	No	Yes	No
Target required	Yes	No	Yes	Yes

3.5.2 Market research conclusion

After a comparison and in depth study of the systems available, it was concluded that there are no current systems on the market that can fulfil the required criteria expressing the need for this project to be undertaken. The systems researched are lacking in the following ways:

- No provision or capability for an operator HMI interface for clear display of crane location.
- No provision of precise distance measurement reading (3 relay out puts only for warning stop and function)

- No capability for expansion and crane control (other than 3 relay output)
- No capability for further upgrades such as variable speed drive control or interrogation by the system
- Non customisable features of control (other than distances of operation for the 3 relays)

3.6 Solutions

In order to provide a solution to the problem it was required for the system to provide the following:

- An anti-collision distance tracking system prototype which can be utilised on all cranes within the cold mill.
- Utilizing a distance sensor and a controller, the sensing device can be mounted on the bridge of the crane and pin pointed on the building wall limit.
- The sensor utilizes an algorithm to calculate the distance and is then transmitted to the controller as a value using either a 0-20mA or 0-10V
- This data can then be utilised to generate a real time display of crane location on a HMI along with setting up specific "Zones" to trigger warning alarms and warning indication to the driver in the cab.
- If the crane continues to move and enters the "Danger Zone", the system will trip sending an output from the PLC to a crane trip contact in the main crane control code preventing collision.

3.6.1 Solution 1 – Laser Distance Tracking with PLC Control

This solution utilises a laser distance sensor and a PLC for control logic. The laser can be mounted on the bridge of the crane and pin pointed on the building wall limit. As seen in figure 31

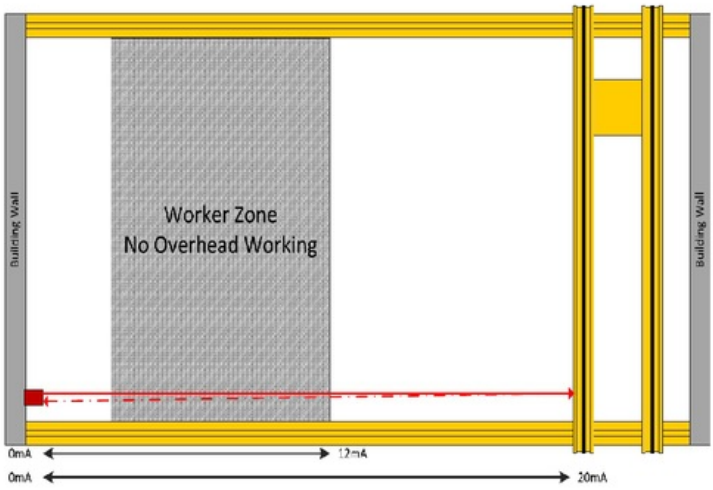


Figure 31 - example of laser utilised for crane to wall sensing (26)

3.6.2 Solution 2 – Laser Distance Tracking Using PIC Microcontroller

This utilises an ultrasonic sensor for distance measurement to provide a 4-20mA signal to the PIC for control.

3.6.3 Solution 3 – Ultrasonic Distance Tracking Using PIC Microcontroller

This utilises an ultrasonic sensor in place of a laser and a PIC for control. The sensor would provide a 4-20mA signal for distance to the PIC and would be mounted the same as seen in figure 31.

3.6.4 Solution Selection

The solution selected for this project is solution 1. This is for the following reasons:

- PLC's are re-programmable allowing for additional code to be added with ease
- Complex logic can be used without the need for complex wiring
- PLC software allows for the use of multiple devices with ease such as timers and counters.
- Analog and digital I/O is freely expandable allowing for multiple sensors to be utilised should further expansion be required. A PIC does not allow for easy expansion of the system.
- A PLC allows for the integration of a HMI with functional control allowing the objectives of the project to be attained.
- Lasers provide very high accuracy reading with high reliability whereas ultrasonic sensors have the potential to falsely respond to interference, this is a major issue as the system is going to be implement in a heavy industrial sector.
- Lasers offer very long distance measurement (up to 20km as shown in figure 21 for TOF method) should further distances be required.

Chapter 4 - Research methodology

4.1 Research onion

In order to ensure the most effective and beneficial research was conducted for this project it was necessary to implement a research methodology. Many methods can be used for doing this but it was decided that the 'research onion' would be utilised. The research onion was developed by Saunders et al. (2007) and illustrates the stages that must be covered when in the process of developing a research strategy. There are 5 main categories to the research onion namely research philosophy, research approach, research strategy, time horizons and data collection methods. Within each of these categories there are different methods to utilise. The selection of these utilised for this project can be seen in the following sections

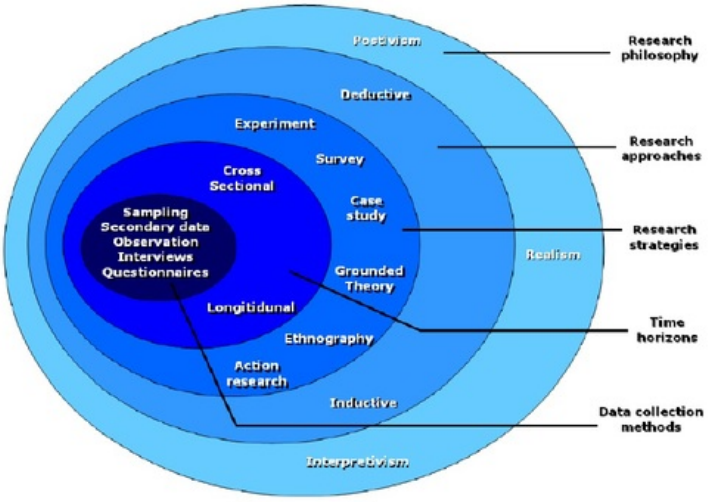


Figure 32 - The research onion

4.2 Research Philosophy

The intended philosophy of this project was to take a positivistic approach. As this project saw the installation of new equipment, certain aspects of the research required to be carried out was based purely on theoretical operation, for example, laser theory. This was a positivistic approach, as it had the advantage of being fast and economical. Once the equipment is installed, any data produced will be quantitative, consisting of hard, specific

data. This has the benefit of being both highly reliable and valid as the equipment will be in its purposed environment giving real-time feedback.

4.3 Research Approach

It was intended to take a deductive approach to this project. As previously mentioned, there is new equipment, namely a PLC, laser and all related hardware to be installed. It is intended for this to give added benefits to the process line by not only reducing crane collisions and hence maintain production but by also providing a user friendly interface for the crane drivers to carry out their tasks with added ease and security. The theory has therefore been assessed prior to installation and will be evaluated where possible once the installation has been carried out.

4.4 Research Strategy

The primary methodology strategy that was utilised in this project is that of document analysis. It was required to conduct research into the theory and operation of the new equipment to be installed along with gaining a clear understanding of the theory behind the plant it will be controlling. As this project is purely providing proof of principle, it was necessary to gain a clear understanding of the theory behind technology that would be utilised if the project were to be implemented in the real world. This was all obtained from published documents and applied to the project.

4.5 Time Horizon

This project primarily adopted a cross sectional horizon, as data collected from the system will be a snapshot of the performance at a certain time. As the data collection will be of the sensor performance under different variables such as environment and surface finish at a specific time this is the appropriate method to use. Unfortunately, due to the nature of this method, the most accurate results cannot be guaranteed as it does not allow for a collection of data over an extended period and results will be based purely on the test conditions set at that time. However as the study is not intended to examine a change over an extended period this is the appropriate method.

4.6 Data Collection

The data collection is this report consists of both primary and secondary data. For the initial stage of the research, secondary data makes up the majority of the research as it is necessary to gain an understanding of the theory and principles behind the technology intended to be utilised. The research also consists of primary data as scientific studies already conducted provide a good insight into how the theory applies to a real situation,

Chapter 5 – Design & Implementation

5.1 Hardware Selection

It must be noted that the requirement stated in this section are refer to the minimum required to meet the project objectives. As the project will be required to expand, a decision was made to ensure that the system allows for overshoot and expansion.

5.1.1 PLC Requirements

5.1.1.1 Analog inputs

1 x analog 0-10V (for laser feedback)

5.1.1.2 Digital Inputs

1 x estop

1 x on/off switch

1 x override switch

5.1.1.3 Analog outputs

No analog outputs required (For current system spec, liable for change under further work however extra signal modules can be purchased as and when required)

5.1.1.4 Digital Outputs

1 x trip lamp

1 x healthy lamp

1 x warning lamp

1 x buzzer

1x laser

5.1.2 Communications

Ethernet/Profinet to communicate with HMI.

5.1.3 Power

Input 240V mains @50Hz

Output 24V DC @2.5A

5.1.4 PLC Requirement Summary

Analog Inputs	1
Analog outputs	0
Digital Inputs	3
Digital Outputs	5
Communications	Profinet/Ethernet
Power	240v/24VDC
HMI Compatible	Yes

5.2 PLC Type Selection

Unitary

The Unitary PLC is an all in one system in a specific housing, which usually contains the Power Supply, for the unit, the central processing unit, Input and output cards all in the single system unit. The unitary system is the simplest of the 3 and is usually standalone with no or very few upgrade capabilities. The size of the unit lends itself to be mounted close or near to machines that is controlling

Advantages: Cheap and reliable

Disadvantages: non- expansive, limited number of outputs and inputs.



Figure 33 - unitary PLC example

Modular The modular PLC is an adaptable unit unlike the unitary based systems. The modular system allows for a custom PLC system to be built for the job in hand and is expandable. **Advantages**: Upgradeable, expandable **Disadvantages**: expensive compared to Unitary limited expansion	 **Figure 34 - Modular PLC example**
Rack Mounted The rack mounted PLC is similar to the modular PLC in its ability to be adapted for the purpose it is being installed. It is constructed primary from the rack up. The rack acts as the communications hub between each component card. These PLCs are generally completely expandable. **Advantages**: expandable, limitless configuration, Upgradeable, isolated cards **Disadvantages**: expensive initial costs	 **Figure 35- Rack mounted PLC example**

5.2.1 Selection

It has been decided to select the modular type PLC as this provides the adaptability and expansion capability without the high initial cost and large size of a rack mounted PLC.

5.3 PLC Selection

There are a number of PLC's available to purchase from TATA Steel recognised suppliers. Although there are many different types available, a contract is currently held with Siemens as a preferred supplier. Some of the PLC options which can match the specification are listed below:

Gem80 • Very Outdated • Complex microprocessor circuits • Runs outdated software ladder logic • Does not support structured text or function block. • Rack mounted	 **Figure 36 - Gem80 PLC**
Allen Bradley SLC-500 • Demands on line editing • Outdated • Does not support structured text or function block • Must have processor offline to write to eeprom • Rack mounted	 **Figure 37 - Allen Bradley SLC-500**
Siemens s7-1200 • One programming software • Extensive built in hardware • High performance versus price • Global product line. Most accepted and up to date software. • Modular	 **Figure 38 - Siemens s7-1200**

As the Gem80 and Allen Bradley are both rack mounted, they are too large for this project along with having many other disadvantages as listed. The PLC of choice is the Siemens s7-1200.

Siemens s7-1200 Selection

	CPU 1211C	**CPU 1212C**	**CPU 1214C**
Memory	50kB	75kB	100kB
Digital inputs	6 x 24V Digital inputs	8 x 24V Digital inputs	14 x 24V Digital inputs
Outputs	4 x 24V DC Outputs or 4 x RLY	6 x 24V DC Outputs or 6 x RLY	10 x 24V DC Outputs or 10 x RLY
Analog inputs	2 x 10 bit 0-10V Analog input	2 x 10 bit 0-10V Analog input	2 x 10 bit 0-10V Analog input
Expansion	Expandable to 3 CM	Expandable to 3 CM & 2 SM	Expandable to 3 CM & 8 SM

The CPU of choice is the 1214C as this provides the best capability for expansion which will be a requirement under further work.

5.3.1 Power Supply Unit (PSU)

The Power Supply unit provides the PLC system with a controlled voltage, usually 24vdc. The PSU creates separate voltage rails for different purposes such a12v rails for the processor unit. As the Siemens s7-1200 has been selected, the power supply that must be utilised is as follows:

Simatic S7-1200 Power Module (27) • Supply 176-264V • Output 24V DC (controlled) • 83% Efficiency (12W loss) • Supply Current 0.67A	 **Figure 39 - s7-1200 PM1207 (27)**

5.3.2 Digital Input Card

Although the PLC selected meets the requirements for the initial design, a conscious decision has been made to incorporate an extra digital input module. This will allow for easy further expansion of the system when installed on the crane.

Digital Input SM 1221	
• 24v DC • 8 DI • Sink source input	 **Figure 40 - SM1221 (28)**

5.3.3 Network Component

The Network component allows the PLC to communicate with the outside world. As there are multiple devices required to be connected to the PLC it was necessary to incorporate an unmanaged switch. This module was selected as it is the lowest cost solution for implementing local Ethernet networks with a SIMATIC S7-1200 and it reduces assembly costs and mounting space.

Switch module CSM 1277	
• Connects s7-1200 & 3 Ethernet users • 10/100 MBIT/s unmanaged switch • 4 RJ45 ports • 24VDC power supply	 **Figure 41 - CSM1277**

5.4 Sensor Selection

SickDME2000 • +/-5mm accuracy • 0.1-130m range • 1/10000mm resolution • Requires reflector • Red Light class II laser • Programmable parameters • Pre failure signalling output • output 4-20mA • Large size (138x105mm • TOF measurement	 **Figure 42 - SickDME200 Laser (29)**
Sick DME 4000 • Multiple measurement and positioning from 0.15m to 220m • Visible red laser class II • 2ms output rate • Variety of interfaces • Large size 166 x 85mm • Expensive (£300-£400) • Requires diamond grade reflective target • 0.055mm resolution • TOF measurement	 **Figure 43 - Sick DME400 Laser (30)**

IFM 01D100	
• Easy disconnect • Visible red class II laser • 0.2-10m range • Analog 0-20 or 4-20 mA output • Visual mm display • Compact size (45 x 55mm) • +/-15mm accuracy on white • Readily available due to low cost in comparison • Price £198 • Phase Shift measurement	 **Figure 44 - IFM 01d100 Laser (31)**

The sensor selected is the IFM 01D100. This is due to the following reasons:

1. As concluded in the research, this type laser is more suited to ranges of 0-20m, a longer distance laser is not necessary for this project.
2. Based on the research conducted, Phase shift lasers offer the highest accuracy between TOF and FMCW techniques with just a few mm as seen in figure 22.
3. Readily available whereas other options require fund authorisation and wait time for delivery.
4. Cheapest option whilst meeting required specification at £198.

5.5 Serial Device Server

As the system is required to be suitable for installation on any high bay cranes in Tata Steel, it is required to incorporate a means of communication between the PLC system (Ethernet) and the DC speed control drives on the cranes (RS-232 serial). The device selected to do this is the recommended standard for Ethernet to serial switches in Tata Steel UK.

NPORT MOXA 5410 (32)	
• 10/100M auto sensing Ethernet • 4 serial ports (RS-232) • 15kV ESD surge protection	 **Figure 45 - MOXA NPORT 5410 (32)**

5.6 HMI Selection

In order to generate an operator control screen, the Siemens Simatic comfort HMI was utilized. This HMI allows for the configuration of a user friendly operator control screen with the capability of starting and stopping the system, displaying the required data and offering visual representation of the crane location. This was the screen provided by the University for the Project.



Figure 46 - Example Siemens HMI

5.7 PG/PC Device Selection

In order to carry out the programming of the system a PG/PC device was required. This was in the form of a SIMATIC FIELD PG running Windows 7 Professional. This was the programmer of choice as it is Siemens own recommended PG and provides the most up to date software (TIA PORTAL V13) for carrying out this project.



Figure 47 - SIMATIC FIELD PG (33)

5.8 Communications

The S7-1200 supports PROFINET, PROFIBUS and AS-Interface (ensuring the required signal modules have been purchased).

5.8.1 AS- Interface

This is a networking system for binary sensors and actuators in the field area. This protocol allows is now in place where a direct field bus was once not technically possible or not economical. This method is therefore not suitable for communication on the cranes and has not been selected for this project

5.8.2 Industrial Ethernet

This is a cell level network according to the international standard IEE 802.3 (Ethernet) and is designed for industrial use. It allows extensive open network solutions and guarantees a high transmission rate and is suitable for installation on a crane.

5.8.3 PROFINET

This is the standard for communication applications in the field level and enables the interfacing of distributed field devices through industrial Ethernet with the TCP/IP protocol. PROFINET is therefore the selected communication method of choice.

5.8.4 PROFIBUS

This is the bus system for cell networks with a limited number of nodes. PROFIBUS guarantees openness for the communication of components from other manufacturers that conform to the standards. The PROFIBUS accessing procedure functions according to "Token Passing with subordinate Master-Slave" procedure. As a result distinction is made between active and passive network participants. This method could be selected however the decision has been made not to as industrial Ethernet (PROFINET) will suffice.

5.9 Circuit Design

Figure 48 shows the circuit design for the system. It can be noted that the extra digital input card has been excluded from the design as this was not required for the project under the project specification and will only be utilised once the system is installed on the crane itself.

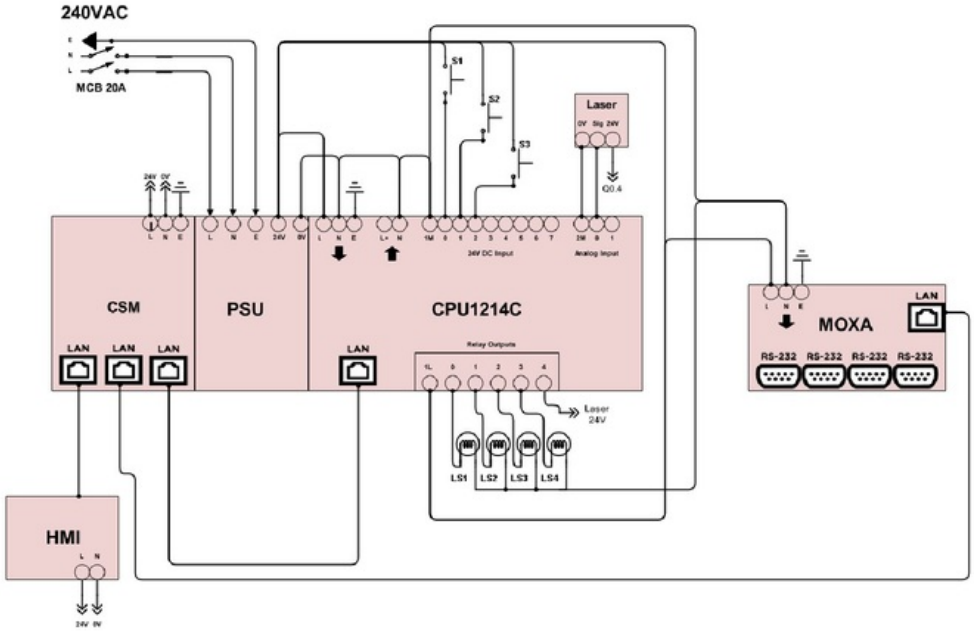


Figure 48 - Circuit Design

5.9.1 Laser Module connection

The laser module requires a 24V supply which is taken from the regulated s7-1200 power module and the 0v is connected to the 2m port. The signal pin is connected directly to the analog input '0' of the PLC as seen in figure 49

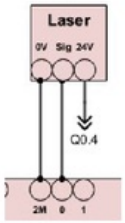


Figure 49 - Laser module connection

The analog input ports of the selected PLC are limited to a voltage input from the sensor. However if a current signal were to be required from the sensor, this could be converted to a voltage signal suitable for the PLC by connecting a 500Ohm resistor in series. This would have the effect of providing a 2-10V signal which would allow for easy detection of a signal break at 0V as seen in equation 19.

$$V = R \times I$$

$$V = 500 \times 0.02 \text{ (20mA)}$$

$$V = 10$$

$$V = 500 \times 0.004 \text{ (4mA)}$$

$$V = 2$$

Equation 19

Analog signals offer the advantage of increased immunity to noise and interference with the primary advantage being that a signal loss can be detected easily. At minimum distance value, a 4mA signal should be present, with a 0mA signal indicating signal loss. A 0-10V signal however does not usually accommodate for such a circumstance, however in the application of this project, a 0V signal would represent the trip distance between the crane and wall resulting in an alarm and trip function. As a 0V signal would initiate a trip due to either signal loss, or minimum distance signal, the outcomes required are the same.

As the 01d100 laser selected provides either a 4-20mA or a 0-10V signal, it was decided to utilise the 0-10V signal as the same protection is offered against signal loss and the potential for loss of resolution due to conversion is mitigated.

5.9.2 Inputs

The required inputs for the system obtain the 24V power from the PSU to ensure a safe regulated voltage is supplied to the PLC. These are then connected as seen in figure 50, with 1M as the 0V:

Drawing Label	Input Address	Function
S1	I0.0	E-Stop
S2	I0.1	On/Off Switch
S3	I0.2	Engineer Override switch

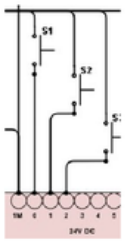


Figure 50 - Circuit design inputs

5.9.3 Outputs

The relay outputs from the PLC have been connected as seen in figure51. As the PLC selected (DC/DC/RLY) utilises relay outputs rather than transistor switched 24V, Port 1L should be supplied with the voltage required by the output devices. The benefit of Relay outputs is that they are non-polarized allowing it switch AC or DC allowing for easier connection to external devices. If transistor outputs were utilised, only DC current can be switched and typically cannot switch as large a load as the relays. Therefore, it is suitable to switch the 3 output lamps and 1 buzzer directly from the PLC.

Drawing Label	Input Address	Function
LS1	Q0.0	White Lamp (Warning)
LS2	Q0.1	White Lamp (Warning)
LS3	Q0.2	Red Lamp (Trip)
LS4	Q0.3	Buzzer
LS5	Q0.4	Laser

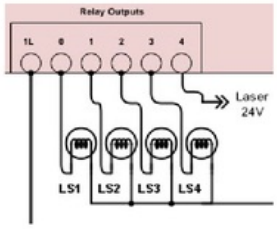


Figure 51 - Circuit design outputs

5.9.4 Supply Voltage

As is required to power the system (PSU) from 240V mains, it was required to incorporate circuit protection. The protection selected is 2A type B MCB. This provides ample current to be supplied whilst offering a suitable protection for the cable and PSU.

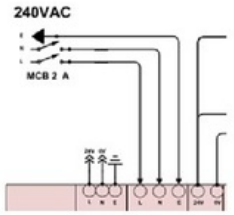


Figure 52 - Supply voltage circuit design

5.9.5 Network Connections

As the switch selected is an unmanaged Ethernet switch, the HMI, PLC and MOXA have been connected via LAN ports. There is also provision on the switch to allow the programming device to be connected without any alterations to the circuit.

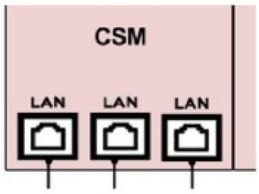


Figure 53 - Network Connections

5.10 Block Circuit Design

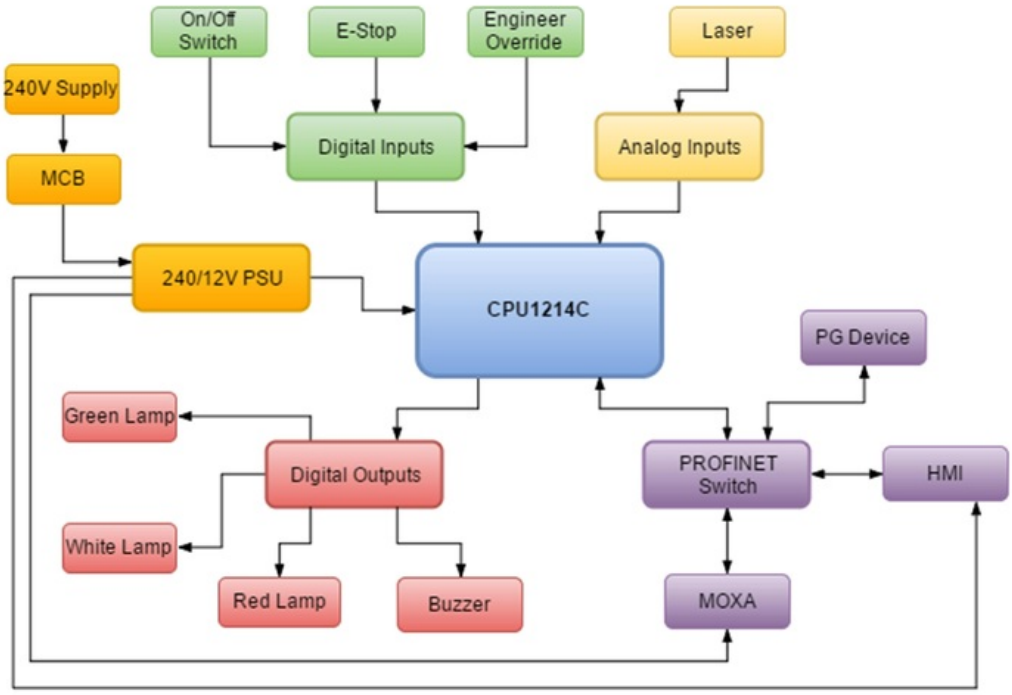


Figure 54 - Block circuit diagram

5.11 Panel Design

As the system is to be purpose built for proof of principle with the capability to later be installed on a crane, considerations had to be made to ensure it was suitable for being portable. The design allows the laser to be mounted to the panel without the need for external equipment with all system functions local to the panel.

The panel incorporates 3 visible lamps for easy identification of current status, green to indicate healthy (crane is within working zone), warning (crane is in warning zone) and red (crane is in danger zone, trip). An on of switch is included to remove power from the laser (for maintenance or safety reasons). A mains power switch has not been included as this can only be done via the MCBs inside the board to prevent tampering by operators.

The panel includes an E-stop made clearly visible and accessible to comply with regulation 15 of the Safe Use of Work Equipment code of practice laid out by the HSE (34) and an engineer key override switch required for trip conditions. See Figure 55

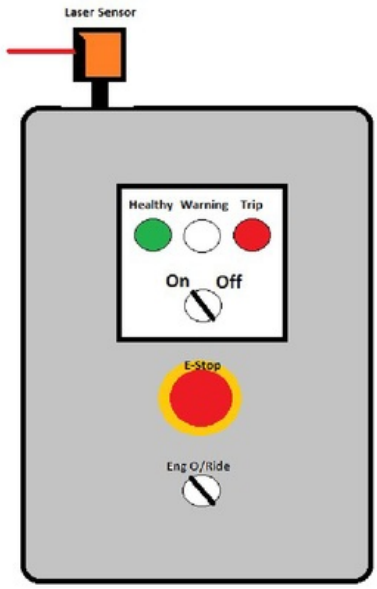


Figure 55 - Panel Design

5.12 Software Design

5.12.1 Programming method

The decision was made to utilise the method of hardware independent programming as opposed to hardware dependant. This means that the software was designed and programmed prior to the installation of any hardware. This gives the advantage of determining if any extra hardware will be required outside the original design specification.

5.12.2 Cyclic Program Execution

On start the CPU will carry out a warm restart (with OB100) when switching power STOP to RUN. This will delete all non retentative bit memories and start the scan cycle time monitoring (this was set at 150ms as this will provide ample scan time, anything longer than this will initiate a PLC trip).

5.12.2.1 Scan Cycle

This operation consists 3 main cyclical operations as seen in figure 56. The program that is to be continuously executed is stored in OB1 with a new cycle starting with the updating of the process images and the processing of the first statement in OB1.

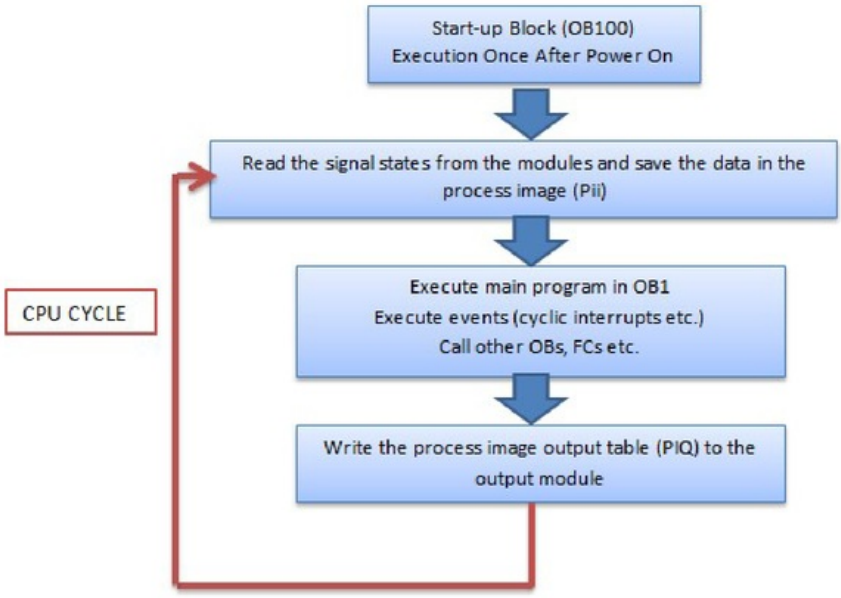


Figure 56- Cyclic program execution

5.12.3 Warm Restart

Warm restart was selected as the default start up condition as this is the industry standard. This will delete the process images (PII and PIQ) with all non-retentive memory. Retentive memories along with all data blocks (to be seen in section 5.16.2) are retained. The program stored in OB100 is executed once and then the cyclic program execution begins.

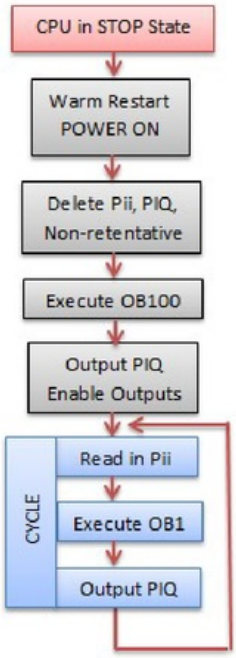


Figure 57 - Warm Restart Cycle

5.13 Program Operation Block Diagram

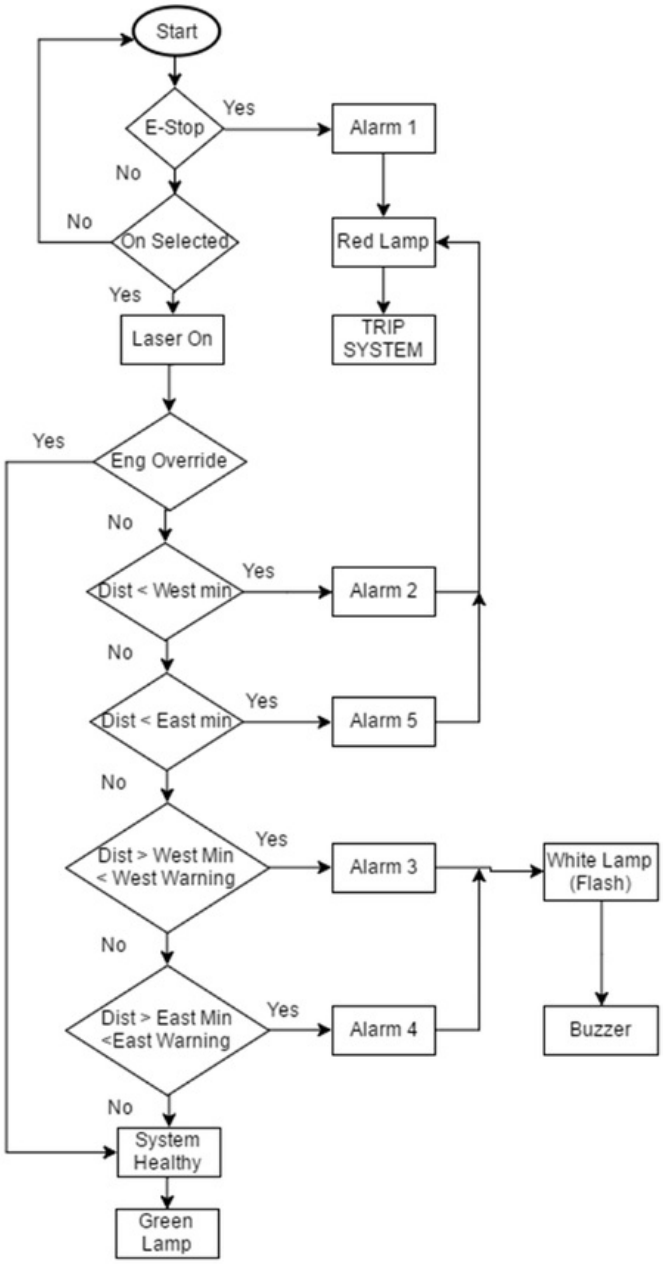


Figure 58 - Program operation block

5.14 Programming Structure Selection

There are 2 main types of programming structure namely Linear and Partitioning.

5.14.1 Linear

Linear programming consists of the entire program being found in one continuous block (OB1).The CPU will then process the individual instructions one after the other. This has the downside of becoming very confusing with masses of code in one main block making specific functions hard to fault find on or add to. It also can have the negative effect of processing the furthest rung in the code over earlier rungs, so higher priority alarms for example would have to be located later in the code than lower priority alarms. This was not an acceptable option for the project as it is not the industry standard.

5.14.2 Partitioned

This consists of dividing the program into blocks whereby every block contains on the program required for solving the task. Further partitioning through networks is also possible. OB1 main block code is kept to a minimum only consisting of instructions to call the required functions in a defined sequence. This is therefore the programming method of choice as this will allow specific functions to be programmed, added and fault found on. This will keep the overall project tidy and allows it to operate in a far more functional manner. This is also the industry standard as this will allow for further programming to be added with ease should it be required, where linear programming poses an issue.

5.15 Addressing in Siemens

Table 3 - Addressing in Siemens

Inputs	I
Outputs	Q
Memory	M
Byte	8 bits (0-7)
Word	2 Bytes (16 Bits)
Double Word	4 Bytes (32 Bits)

5.16 Project Structure

As seen in figure 59.

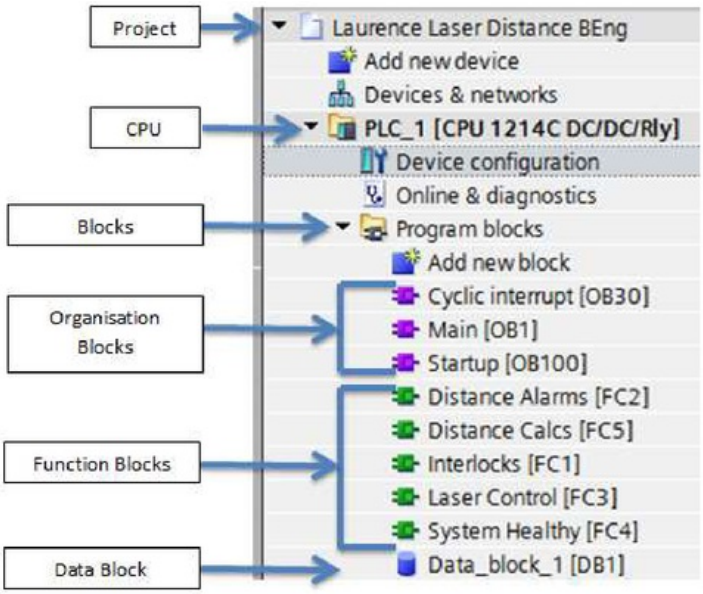


Figure 59 - Project Structure

5.16.1 Organisation Blocks

Organisation blocks (OBs) are the interface between the CPU's operating system and the user program. The operating system will call each OB exclusively. There are various types of OBs some of which have been utilised in this project.

5.16.1.1 Main Block Code (OB1)

As previously stated, due to utilising partition programming, this block is the main program block which purely calls the required functions (see appendix 6, OB1 main block). All other organisation blocks will cycle according to their custom requirements. See figure 60



Figure 60 - Example of OB1 calling "Interlocks" FC

5.16.1.2 Start-up (OB100)

OB100 is an organisational block which is executed once during a warm restart (See Figure 41). Once the block has been executed, it is no longer part of the PLC scan cycle. This block contains any code that is required to be executed prior to the normal main block. As there is no crane safety parameters required for this project prior to the main block (OB1) being executed, this block has been included, but left blank. This will allow for any code required to be added later, once the system is installed on the crane such as drive status, and other crane interlocks.

5.16.1.3 Cyclic Interrupt (OB30)

The cyclic interrupt (OB30) has been utilised to execute the required block at specific fixed intervals. As opposed to OB1 which will continually scan cycle, calling the required functions and blocks, OB30 will run completely independently with the length of the main block scan time having no effect on when OB30 will run. This means that time critical readings such as laser distance (which is required to be read repeatedly) will be read by the PLC at specific intervals regardless of where the main scan is in the cycle. Although the current program scan time is very fast (within 2ms see figure 61), this block has been utilised to accommodate for further code being added in future which could potentially affect the signal recording times if processed in the main block (OB1).

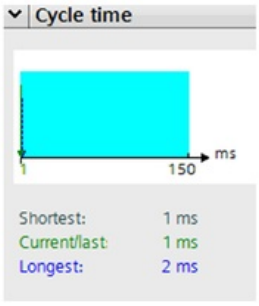


Figure 61 - PLC Scan cycle time

Setting the cyclic time can be seen in figure 62. Note that it defaults to 100ms however this has been set to 2ms to ensure accurate laser measurement. It must also be noted that it was ensured the interrupt time was longer than the time taken for the block to complete a scan otherwise it would trigger before completion.

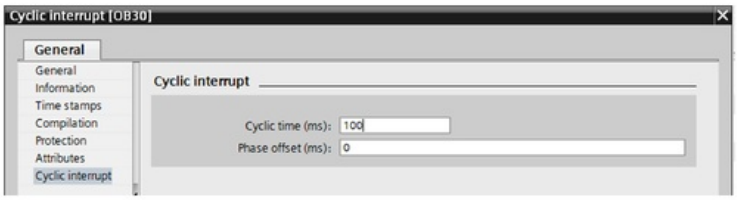


Figure 62 - Cyclic time block setting

5.16.1.4 Laser Signal Conditioning (OB30)

Network 1

First step was to bring in the raw signal from the laser as an INTEGER (IW67 as this can be a word) and convert to a REAL (MD60 as this had to be a double word) using a NORM X block. This maps the value input to a linear scale. The min value was set to 700 as after testing, this was the lowest signal the laser would output before failing (0.2m) and max 27648 as this is the maximum signal (10m).

Next the signal was scaled using a SCALE X block to a range of 0.2 to 10m range and written to "Laser SCALE" (MD64). This is a Real to Real as both values are double words.

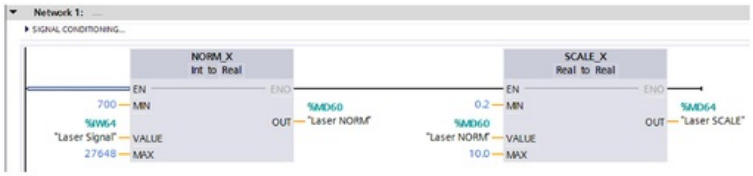


Figure 63 - Laser Signal Scaling

Network 2

With the laser signal scaled, a NORM X block was utilised again to map the distance to a linear scale between 0m and the length of the bay in order to give a value between 0-1 of crane location in relation to the length of the bay. Initially the length of bay was set to a value of 10m, permanently in the code. After testing of the system, it was decided that although this was adequate in relation to the objectives, this did not provide a very adaptable system, required code changes to be carried out every time the system was set up in a different length bay. A way around this was to write the distance values directly to OB1 from the user interface on the HMI (see section "crane operational distances screen") and utilise this value as the maximum distance.

The max value was pulled from DB1 (see figure 64) to allow this value to be utilised in the HMI and as a result, adjusted making the system adaptable for any crane in any length of bay. The output is written to DB1 Laser Pixel Distance NORM.

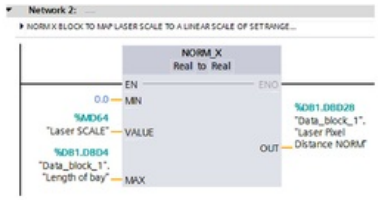


Figure 64 - Laser scaled to length of bay

Network 3

As the output value in network 2 is a REAL between 0-1, it was required to convert this to show the crane location as a percentage of the length of the bay set. This was done using a MUL block to multiply the DB1 Laser Pixel Distance NORM by 100.

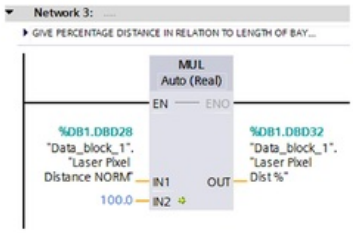


Figure 65 - Network 3 Laser Scaling

Network 4

During testing, problems were encountered as the HMI would not read the percentage value location of the crane. In order to get around this, it was required to convert the output REAL percentage to an INT as the HMI animations were limited to processing Integers. A ROUND block was utilised to do this and write the output to MW4 (word) “Laser Scale INT”.

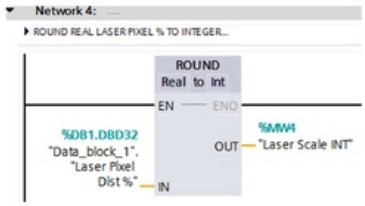


Figure 66 - Network 4Laser Scaling

5.16.2 Data Block (DB1)

In addition to the program blocks, it was decided to utilise a data block to store information about process states and signals allowing it to be processed by the program. Variables can have a permanent storage location in the process image, bit memory area or data block or can be created dynamically in the "L stack" when a block is being executed. The local data stack (L stack) is an area for storing temporary variables whereas data blocks are used for storing values where unlike the L Stack, they are not overwritten when the block is closed or completed.

The DB created can either be an "Instance" where the data can only be used in the assigned function block or a "shared" DB where the data is global to the whole project. The type selected is "shared" as all functions and HMI will require data from OB1. The data can be accessed with bit, byte, word or double word operations.

Data_block_1

	Name	Data type	Offset	Start value	Retain	Accessible f...	Visible in ...	Setpoint
1	Static							
2	Min Laser Dist EAST	Real	...	1.0		☑	☑	☑
3	Length of bay	Real	...	10.0		☑	☑	☑
4	Min Laser Dist WEST	Real	...	1.0		☑	☑	☑
5	Warning Zone EAST	Real	...	2.0		☑	☑	☑
6	Warning Dist WEST	Real	...	2.0		☑	☑	☑
7	Alarm Block	Word	...	16#0		☑	☑	
8	Engineer Override KEY	Bool	...	false		☑	☑	
9	Engineer Override HMI	Bool	...	false		☑	☑	
10	West wall distance	Real	...	0.0		☑	☑	
11	Laser Pixel Distance N..	Real	...	0.0		☑	☑	
12	Laser Pixel Dist %	Real	...	0.0		☑	☑	
13	Warning Tag HMI	Bool	...	false		☑	☑	

Figure 67 - Data Block DB1

5.16.3 Functions Code Programming

As partitioned method has been selected as the method of programming it is necessary to utilise functions within the code to be called in OB1. Functions are code blocks without dedicated memory but can call for data from DB1.

5.16.3.1 Laser Control (FC3)

If on/off switch (I0.1) is made, and estop is not active (I0.0) (wired normally closed on button so fail safe), switch on laser (Q0.4) and retain.

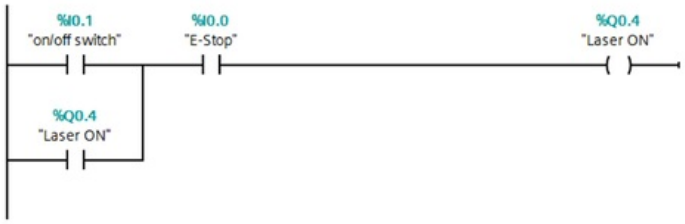


Figure 68 - Laser control code

5.16.3.2 Interlocks (FC1)

The interlock contact (M0.0) will be used in the main crane control code (Not this system) to allow crane movement. If this is dropped out then the crane will be inhibited. Any trip conditions will bring on Red Lamp (Q0.2); this will drop out the interlock.

If the trip is caused by entering a “Danger Zone” the crane will remain tripped until it returns to the safe zone. Engineer override allows the interlock to be switched healthy to allow crane movement out of the trip zone (this is done by means of either a key switch on panel, or HMI password protected function). These are written to DB1 to allow HMI functionality.

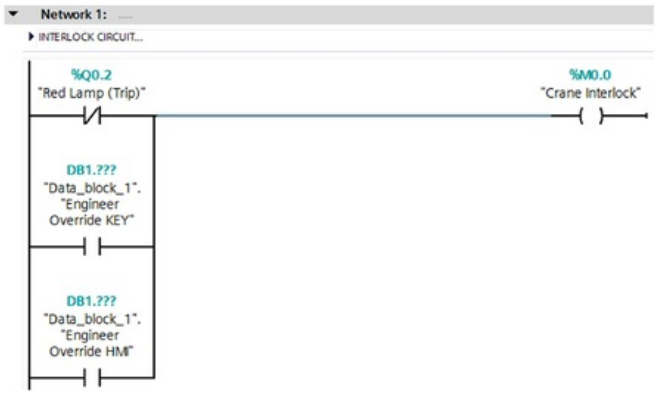


Figure 69 - interlock circuit code

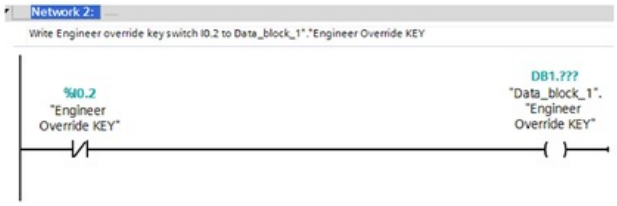


Figure 70 - Engineer override code

5.16.3.3 Distance Calcs (FC5)

As a single laser is being used, only one distance measurement is given (East Wall). Originally the design only required this as all trip distances were set to a distance from the laser target. This was decided against as it does not allow for easy adaption of tripping zones dependant on the length of bay the system is installed. The distance to the west wall needed to be calculated dependant on the length of the bay (set by engineer)

The SUB math function was used to subtract “Laser Scale” from “Length of Bay” written to DB1 by HMI to give West wall distance. Alarms for West distances are therefore set according to this value.

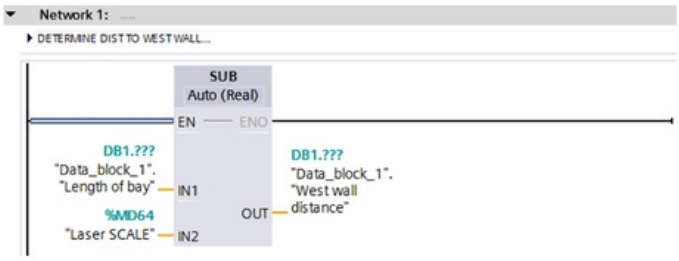


Figure 71 - West wall distance code

5.16.3.4 Distance Alarms (FC2)

Initially, it was decided to utilise the common method of activating an alarm warning whereby when an alarm state is active, the integer related (set in code) will write to the alarm word and displayed on the HMI. After consideration, it was decided this method although acceptable, had the following limitations:

1. Only one alarm can be displayed at a time reducing fault finding capabilities
2. The alarm furthest in the code, takes priority and is displayed
3. No information is logged with the alarm, such as time and date
4. A separate key is required to explain alarm numbers
5. No logging of alarms.

To overcome these limitations a new method was utilised. The alarms are set by triggering the bit associated with that alarm in the “Alarm Block” word located in DB1. For example, E-stop alarm is triggered by making bit 0 of “Alarm Block”. As can be seen only the bits 0-4 of “Alarm Block” have been utilised which allows for the more alarms to be easily added once the system is installed and more alarms are required.

The alarms are split into two classes namely errors and warnings. These have been set up under “alarm classes” to ensure the correct machine state is applied once the alarm is activated. This affects how the alarm will be displayed and whether it must be acknowledged. An alarm description could also be tagged to the alarm overcoming the limitation of requiring a key for description. The set alarms can be seen in figure 72.

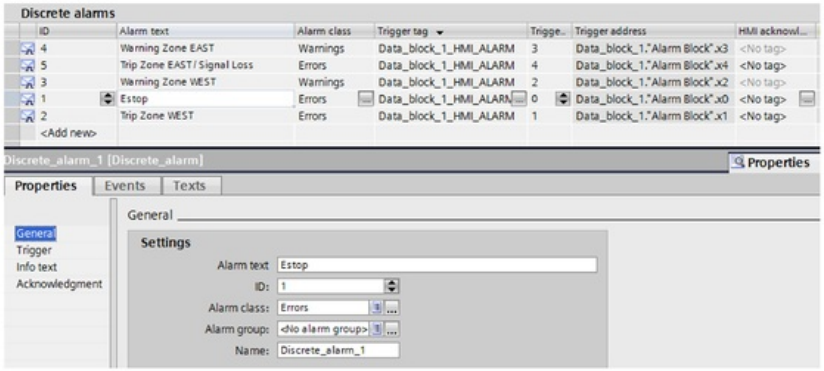


Figure 72 - HMI Alarms set up

5.16.3.5 Warning Zone

The distance alarms function writes the outputs or the alarm conditions to the required bits of the "Alarm Block" word. Example of warning zone west alarm block (figure73) Shows if West wall distance is greater than "Min Laser Dist WEST" and less than or equal to "Warning Dist WEST, set "Alarm Block" bit 2 and "Warning Tag HMI". This will trigger the alarm associated with bit 2 and give the warning tag to the HMI for visual display.

Originally the distances triggers were set values in the code, however the decision was made to change this and allow them to be set and adjusted by the engineer on the HMI. This gives more adaptability to the system.

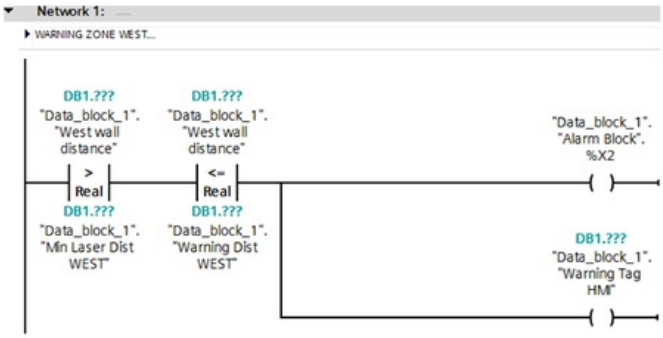


Figure 73 - Warning zone West code

If either of the warning zone alarms are triggered, then the output to Warning Lamp (Q0.1) and Buzzer (Q0.3) is made. M100.5 has been utilised as clock bit (this was set up in the

hardware config) which will continually operate at a frequency of 1Hz. This results in the warning lamp and buzzer pulsing for added warning effect.

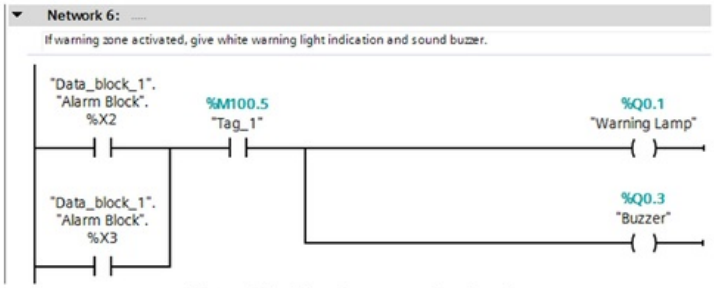


Figure 74 - Warning one output code

5.16.3.6 Trip Zone

Example of trip zone (figure 75) shows if "West wall distance" is less than or equal to "Min Laser Dist West" set in HMI, make "Alarm Block" bit 1.



Figure 75 - Trip zone West alarm code

If any alarms are active, then Red Lamp (Q0.2) will activate, causing crane interlock to fail. As the warning alarms are not deemed critical to trip the crane, Q0.2 is held out by 2 normally closed contacts from the warning alarms. See figure76.

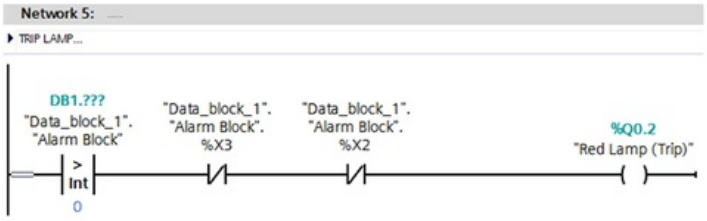


Figure 76 - Trip Lamp Code

5.16.3.7 E-Stop Alarm

As the E-stop pushbutton is wired N/C, the alarm is held out by a N/C contact. The HMI estop is a system stop and in not hard wired so must be N/O. If either of these are pressed "Alarm Block" bit 0 is made. See figure77.



Figure 77 - Emergency stop code

5.16.3.8 System Healthy (FC4)

If the laser is on, the "Alarm Block" word at 0, Laser Scale is greater than Minimum set distance east and crane interlock is healthy, and then Green Lamp (Q0.0) is given.

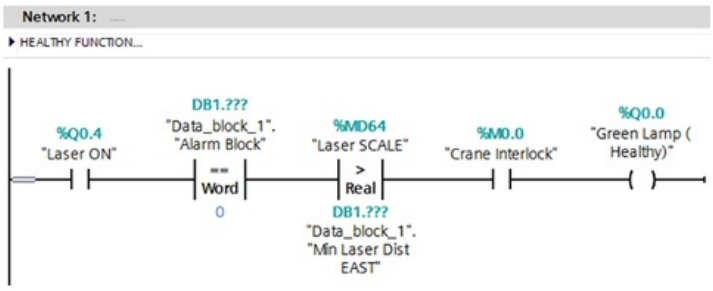


Figure 78 - Healthy function code

5.16.4 Final Program Structure Diagram

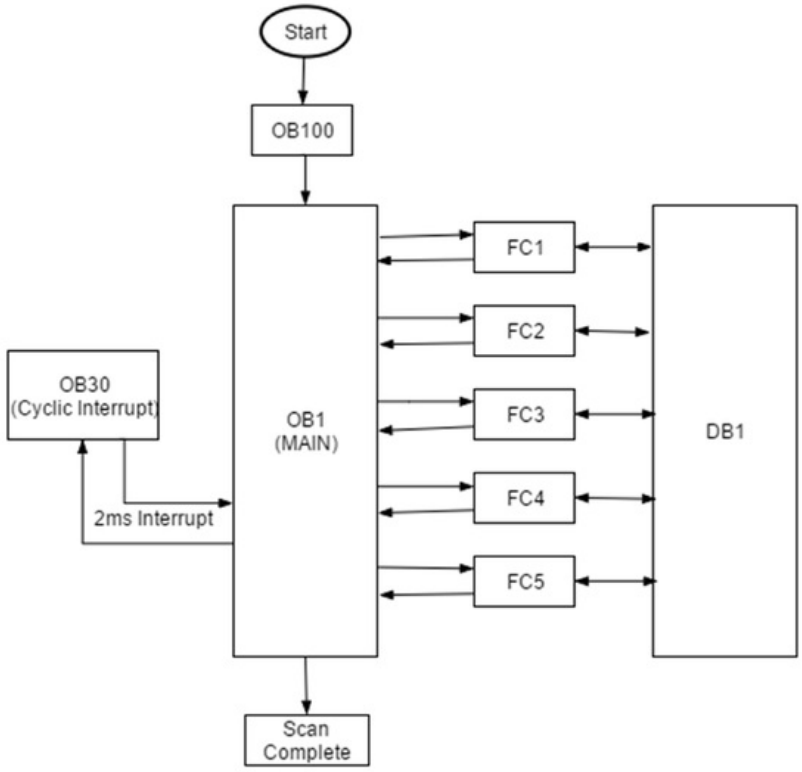


Figure 79 - Final Program Structure Diagram

5.17 HMI Design

This section provides details of the final HMI design.

5.17.1 Root Screen

The root screen is the main operational screen which is intended to be displayed clearly to the crane operator. The main functions of this screen are depicted in figure80. Under healthy conditions, the colour banner will illuminate green with no alarms present. This banner is tagged to "Green Lamp Healthy" in the PLC. The crane will also be displayed within at the correct location within the bay and be within the correct colour coded zone (depending on what the length of bay has been set to). The "Laser On" icon should be displayed with the "Engineer Override" icon not illuminated.

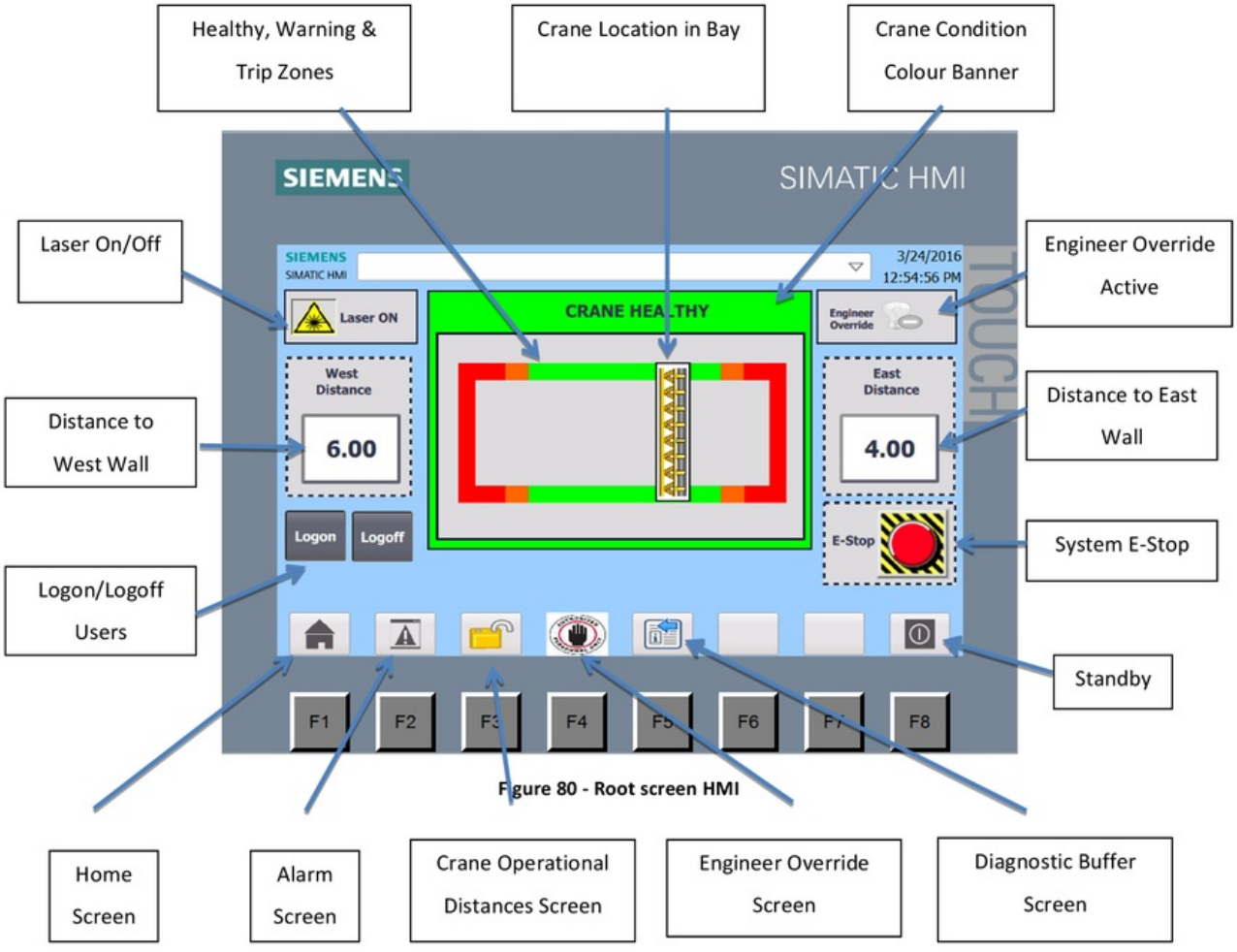


Figure 80 - Root screen HMI

5.17.2 Crane Animation on Root Screen

In order to animate a scaled crane movement in relation to the bay the tag "Laser Pixel INT" was utilised. This HMI tag is written to from the PLC tag "Laser Scale INT" in the cyclic interrupt. As the HMI animations can only utilise integers rather than real numbers, this was a requirement.

The visual start and finish X, Y coordinates were set and a range of 0-100 applied for animation as the signal has already been conditioned in the cyclic interrupt block to give a percentage of the crane location in the bay in relation to the East wall. This is therefore fully adaptable and will automatically scale in relation to the length of bay set. This can be seen in figure 81.

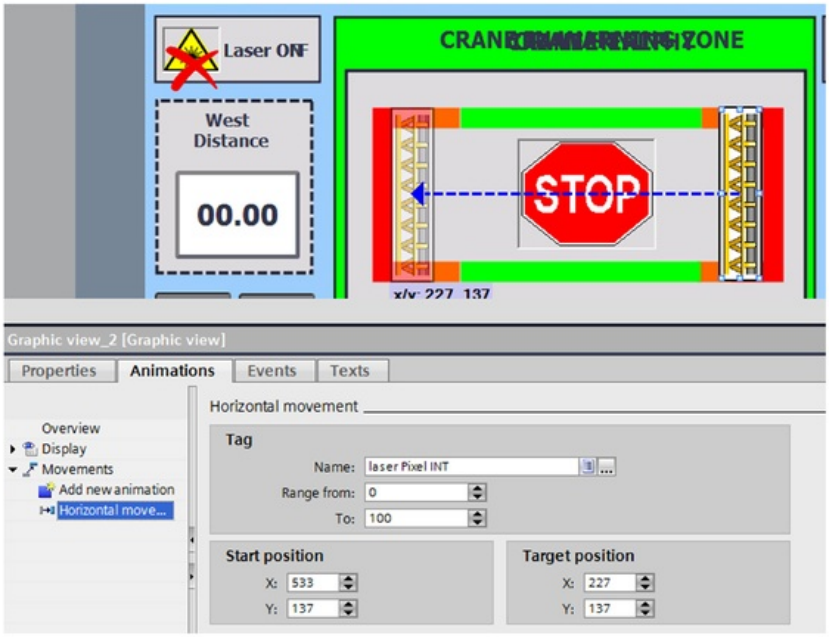


Figure 81 - Crane Animation

5.17.3 Warning Zone Root Screen

When the crane enters the warning zone, the banner will illuminate orange with and a STOP image will appear. Unlike the healthy, and trip images, it was required to write the warning condition to a new tag in OB1 "Warning Tag HMI". This was due to having implications on testing where the HMI would not recognise the PLC tag "Warning Lamp" possibly due to the fact it was being pulsed by the PLC clock byte.

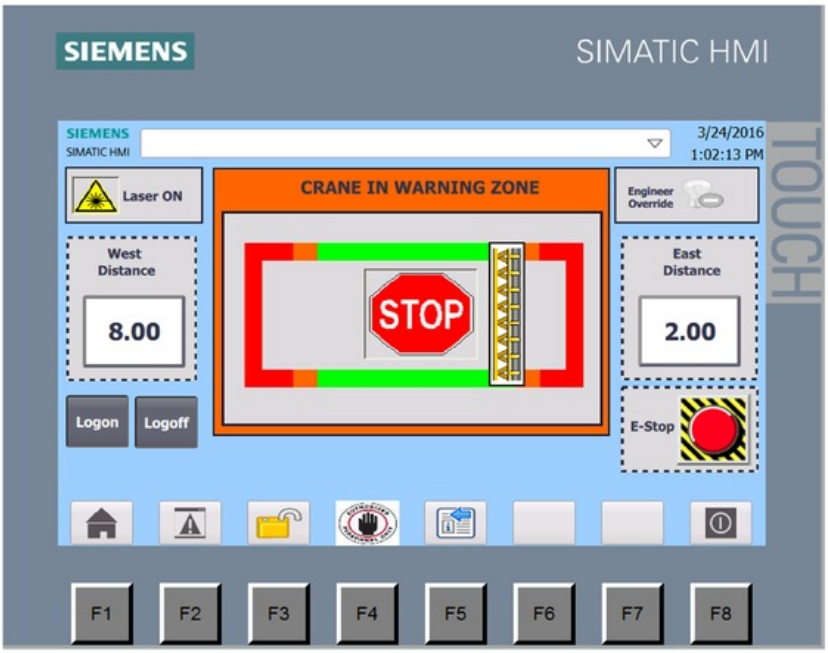


Figure 82 - Warning root screen

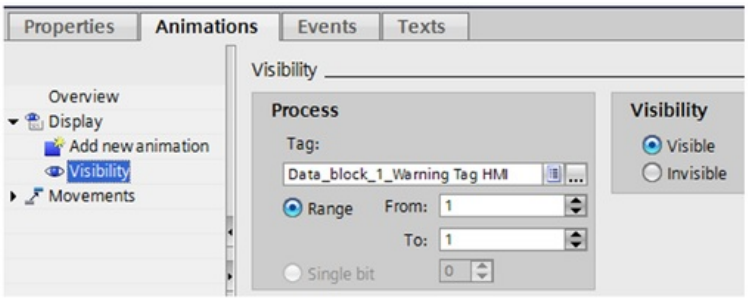


Figure 83 - Warning tag HMI

5.17.4 Trip Zone Root Screen

When the crane enters the trip zone, the banner illuminates red. The crane will remain in this zone as the interlock is lost. As previously mentioned, when either the HMI or panel engineer override is made active, the crane will be allowed to drive without any safety controls. When this condition is made, the engineer override icon will illuminate and a descriptive warning will be made visible to the operator to ensure they are aware the safety controls are de activated.

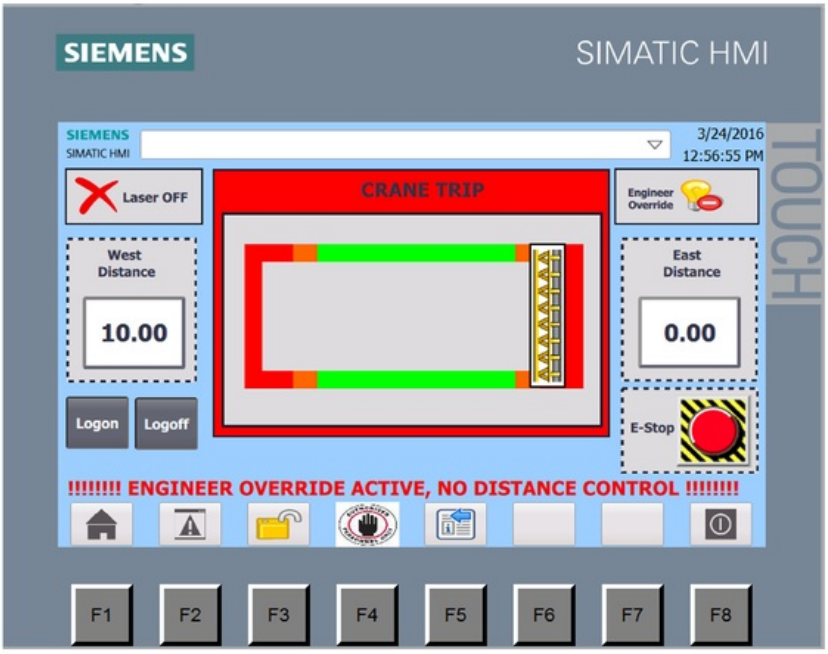


Figure 84 - Trip zone root screen

5.17.5 Active Alarms Root Screen

If any alarms (errors only) are made active then it was decided to flash visual indication of this. A pending alarms banner will appear with all active alarms displayed. A small flashing alarms icon will appear which will remain visible as long as any alarms are unacknowledged. This can be done via the banner or the alarms view page where more detailed description of the alarm is accessible. Initially, all alarms were given error status; however this resulted in the banner appearing during warning conditions and inhibiting operator visibility of crane location and warnings. To overcome this it was decided to give the warning alarms "warning Status" which prevents the banner appearing. The alarms will still activate on the alarm page.

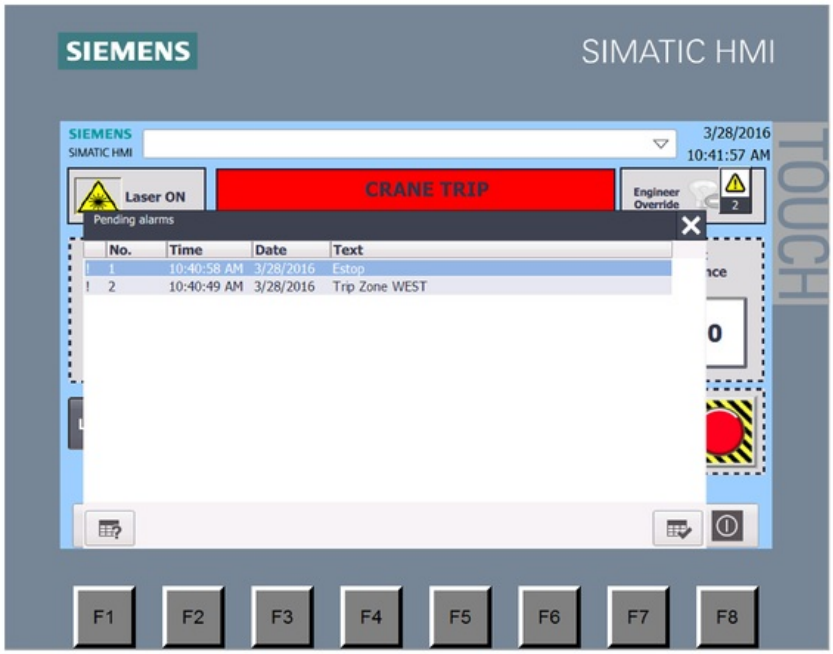


Figure 85 - Active alarms root screen

5.17.6 Engineer Override Screen

This screen provides indication of any active engineer overrides via the cross or tick symbols. Initially this override could only be activated via the pushbutton on the panel however this meant the engineer would have to go back and for between the location of the panel and the HMI whilst driving the crane on override. It was decided a pushbutton on the HMI allowing for the switching of the HMI override with illuminated indication to show if pushbutton is pressed would give improved usability. Access to this screen requires engineer login access and is security protected.

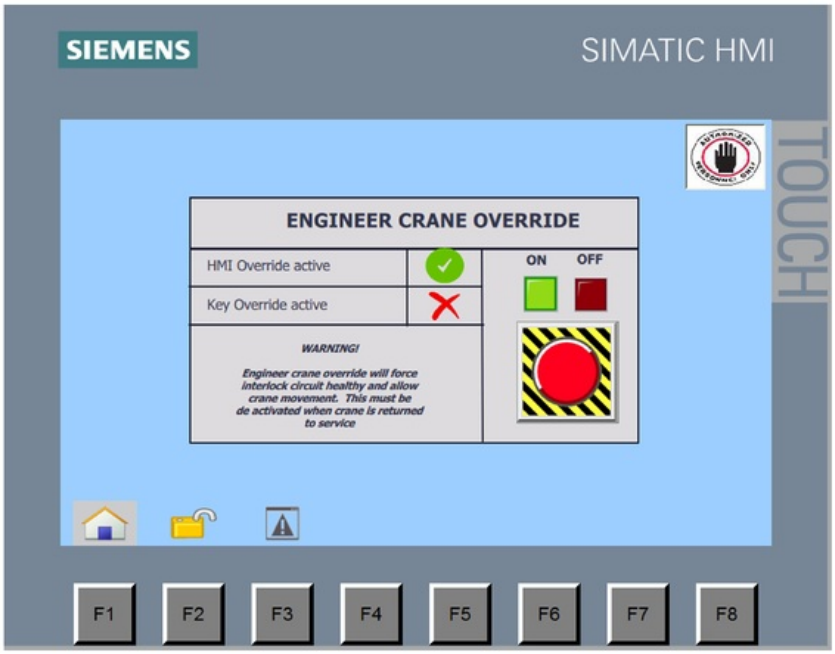


Figure 86 - Engineer override screen

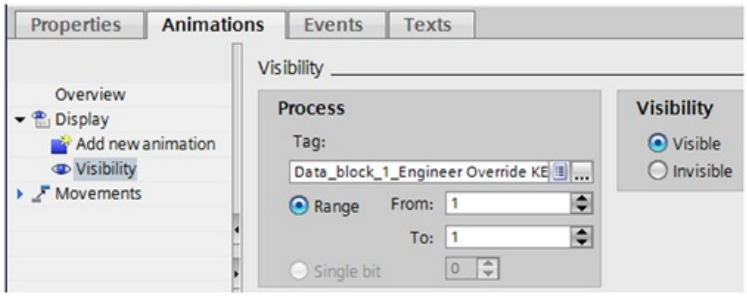


Figure 87 - Engineer override KEY tag

5.17.7 Crane Operation Distances Screen

This screen allows the trip and warning distances to be set. Initially, during the design the distances were fixed in the code at set values of 1m and 1.5m for trip and warning respectively. The length of bay was also set to a value permanent value of 10m. Although this provided an adequate solution, it was not ideal as there is no room for adjustment and the system would not be easily adapted, requiring code adjustments.

A way around this was to write the distance values directly to OB1 which is then utilised in the distance alarm code. This allows programming of the HMI to allow updating of the values. The length of bay also has to be set here, but is defaulted to 10m. This now provides more adaptability of the system. The current laser distance reading to the East wall has also been included as this will aid setting up of the trip and warning distances during crane commissioning. As this is being written to by "Laser SCALE", this will be updated by the PLC every scan cycle, any changes made to this will be overwritten almost instantaneously. This screen is also locked to engineer access and will require a login to prevent any operator tampering for safety reasons.

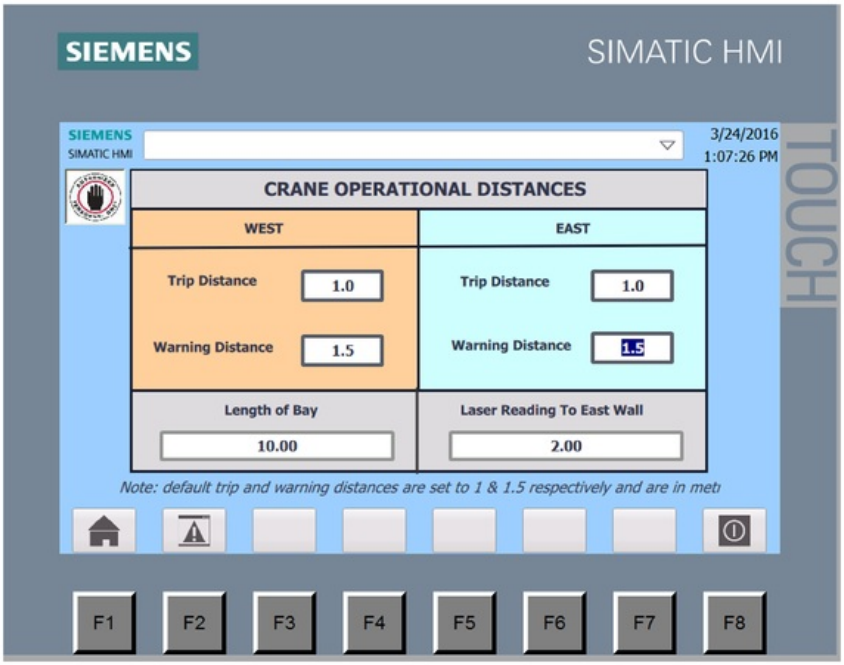


Figure 88 - Crane operational distances screen

5.17.8 Diagnostic Buffer Screen

This screen was included for recognising, evaluating and displaying errors system wide. This will display the diagnostic buffer in the CPU. This ensures previous histories are shown of any system error events. This is a useful aid for engineers when fault finding system on system errors as it provides rapid detection of error causes and the evaluation of events prior to the PLC going into stop. This screen has therefore been password protected to engineer access to prevent operators accessing it.

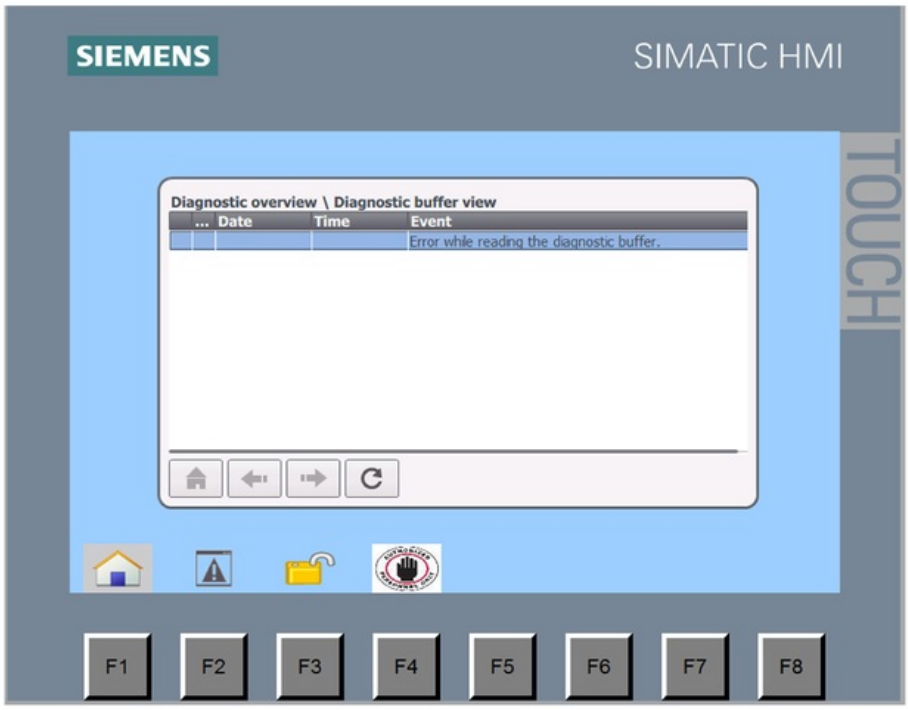


Figure 89 - Diagnostic buffer screen

5.17.9 User Administration

As previously mentioned some operations require specific authorisations. If one of these operations are attempted without a login the box seen in figure 90 will appear. The required login and password must be entered. This can also be accessed via the logon/logoff buttons.



Figure 90 - User Login

The user groups are split into Administrator, Users, and Engineer and specific authorisations were assigned. Individual users were then assigned to the associated group as seen in figure 91. An automatic logoff of 2 minutes was applied to the engineer access to prevent it being accidentally left logged on.

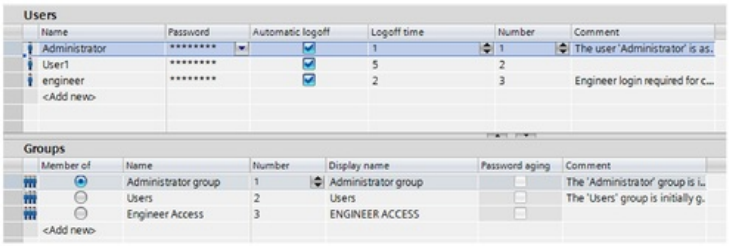


Figure 91 - User Authorisations

5.17.10 Alarm Screen

All active alarms can be viewed on the "Alarm View" screen. These are tagged with a number, time and date of alarm, a current status and text. These can be acknowledged using the right hand button. If the alarm is still present, it will remain visible however the flashing icon will change to a solid state. Any displayed alarms can be selected, and on pressing the bottom left button, an alarm description will be displayed. This will aid in fault finding and help the operator to determine instantaneously what the issue is.

This was a major aim of the project to generate a more efficient user friendly and informative alarm screen rather than a single shot alarm with no descriptions as any alarms/faults can result in downtime with the potential cost of up to £12000 per hour. This method will help operators and engineer to minimise this downtime by clearly displaying what is wrong, and how to correct it.

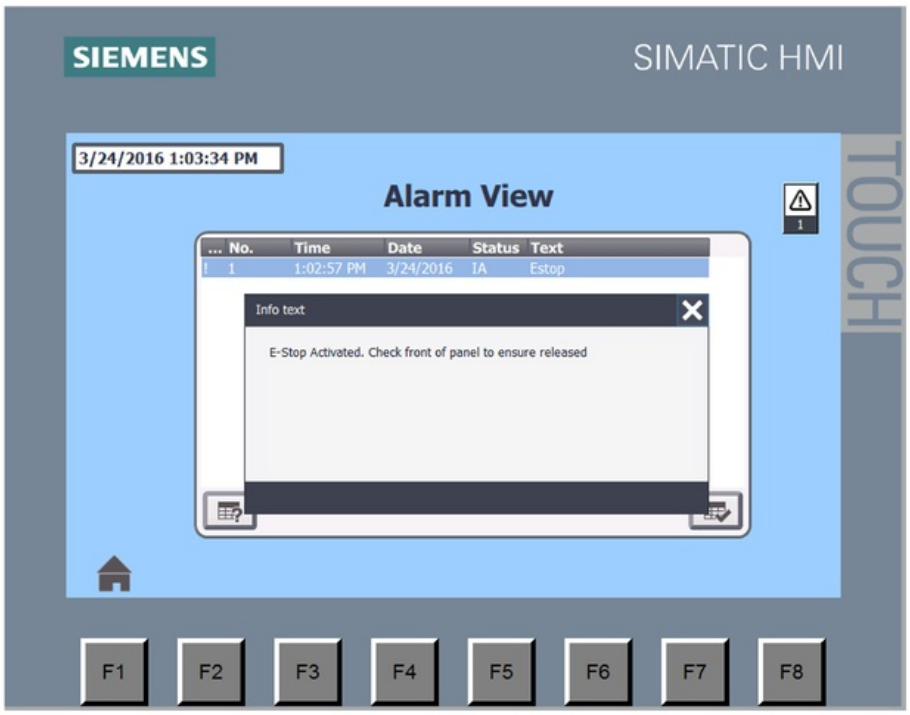


Figure 92 - Alarm Screen

5.18 Panel Build

With the software designed the next stage was to carry out the panel build itself. This was carried out adhering to industry standard practice to ensure ease of fault finding in future.

5.18.1 Intermediate Stage

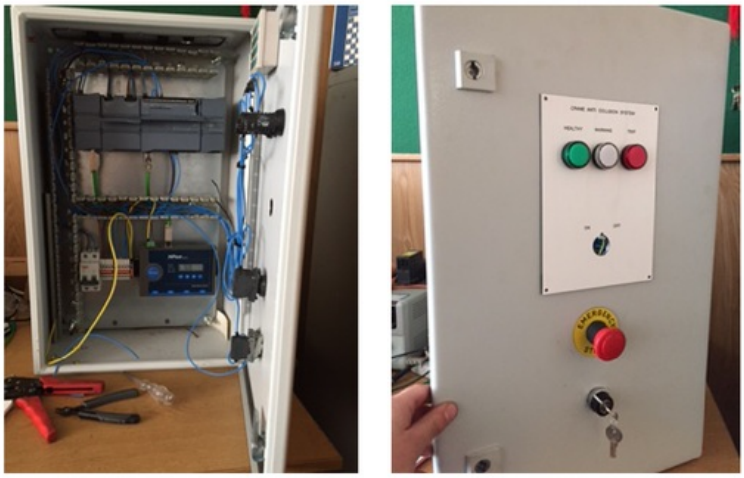


Figure 93 - intermediate stage build progress

5.18.2 Final Stage

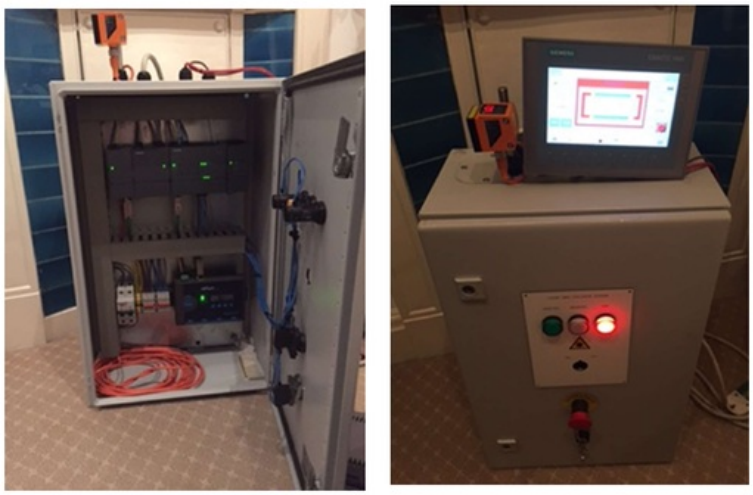


Figure 94 - Final stage build progress

5.19 Build Costs

Table 4 - Build Costs

Item Description	QTY	Each (£)
Following items obtained from TATA Steel UK General Stores		
20mm Stuffing glands (x5)	x1	£5.67
IFM 01D100 Laser	x1	£198.00
IFM System Component Shaft	x1	£13.74
2A Double Pole Breaker	x1	£38.05
E-Stop PB	x1	£21.00
Key Switch Unit	x1	£33.29
Green Lamp 24v	x1	£1.29
Red Lamp 24v	x1	£1.29
White Lamp 24v	x1	£1.29
	TOTAL	**£313.62**
Following Items supplied by UWTSD Swansea, Price Included		
SIEMENS HMI KTP700 BASIC	x1	£600.00
12V Buzzer	x1	NA
	TOTAL	**£600.00**
Following Items Obtained from Parmley Grayham (see quote)		
S7-1200 CPU1214C 14DI/10RLY/2AI DC	x1	£246.75
S7-1200 SM1221 16DI 24VDC	x1	£114.00
S7-1200 PM1207 PSU 24VDC 2.5A	x1	£54.00
S7-1200/1500 MC954 MEM CARD 4MB	x1	£41.25
S7-1200 CSM1277 ETHERNET MODULE 4PRT	x1	£83.25
ETHERNET FC RJ45 180-2X2 PLUG(PK 10)	x1	£93.00
AE ENCLOSURE 380X600X210MM IP66	x1	£50.79
DIN RAIL 35 x 7.5MM x 2M SLOTTED	x1	£5.70
MOXA 4PORT NPORT SERIAL DEVICE SERVER	x1	£316.12
MOXA DIN RAIL KIT	x1	£1.35
	TOTAL	**£1,006.22**
TOTAL PROJECT COST		**£1,919.84**

Chapter 6 - Results & Evaluation

There were primarily two forms analysis required to be carried out in order to assess the success of this project. Firstly, as the system is required to be an accurate distance measurement system providing reliable operation for safety reasons, it was required to analyse and assess the accuracy of the system. Secondly, as the system is going to be installed on a critical functional crane, it is of the highest importance that the HMI and general operation be assessed.

6.1 System Accuracy

Primarily there were two features required to be carried out to assess the system accuracy namely distance accuracy and noise.

6.1.1 Distance Accuracy

For this test, the system distance reading accuracy was tested by taking a reading from the HMI at every 0.5m (measured using a calibrated tape measure) and a white paper target. The results can be seen in table 5.

Table 5 - Distance readings Measured Vs HMI

Distance Readings (m)	
Measured	HMI
0.5	0.52
1	1.02
1.5	1.52
2	2.02
2.5	2.52
3	3.02
3.5	3.52
4	4.02
4.5	4.52
5	5.02
5.5	5.52
6	6.02
6.5	6.52
7	7.02
7.5	7.52
8	8.02
8.5	8.52

9	9.02
9.5	9.52
10	10.02

As can be seen a small error of 2cm is still present in the system HMI display despite the initial signal conditioning carried out in the code to reduce this error. This can be addressed further by tweaking the signal conditioning values again to accommodate for this. This is however more than satisfactory for the project under the current requirements. As seen in figure 93, the accuracy system accuracy follows a linear path in relation to the measured distance and appear to be visually overlapping.

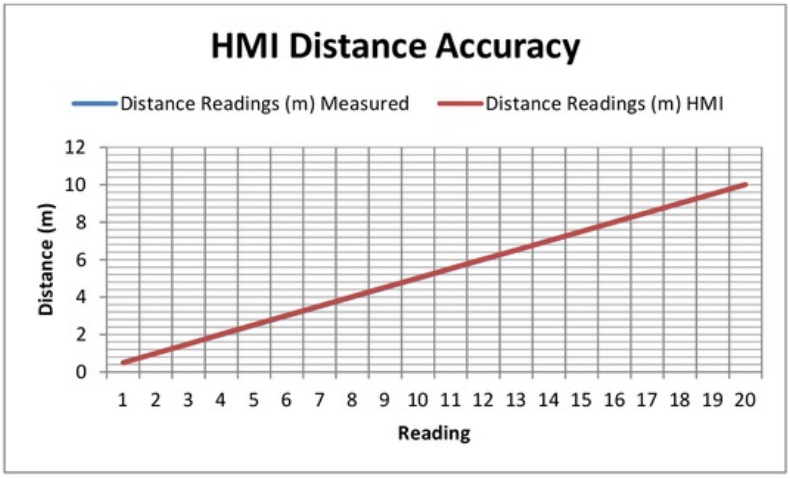


Figure 95 - HMI Distance accuracy graph

6.1.2 System Noise & Overshoot

Laser signal noise on a black surface target at 2077mm can be seen in figure 96.

$$Range\ of\ signal = max - min$$
$$= 2.146 - 2.04$$
$$= 106mV$$

$$Signal\ Overshoot = \frac{range}{2}$$
$$= \frac{106}{2}$$
$$= 53mV$$

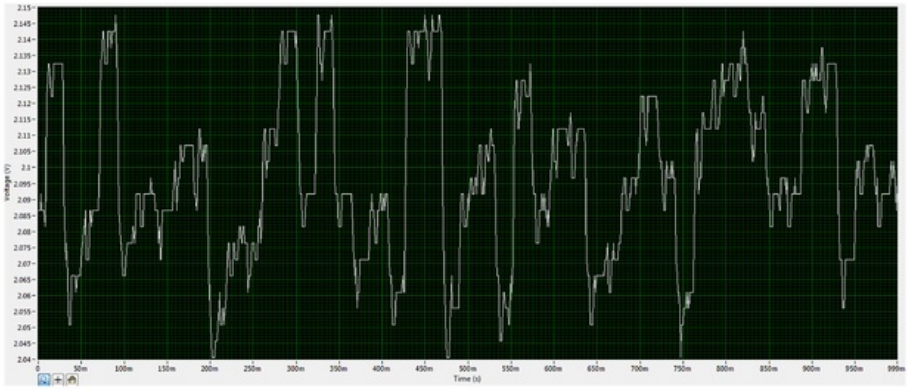


Figure 96 - Laser signal noise on black target

Laser signal noise on a wooden surface target can be seen in figure 97

$$Range\ of\ signal = max - min$$
$$= 2.81 - 2.055$$
$$= 25mV$$

$$Signal\ Overshoot = \frac{range}{2}$$
$$= \frac{25}{2}$$
$$= 12.5mV$$

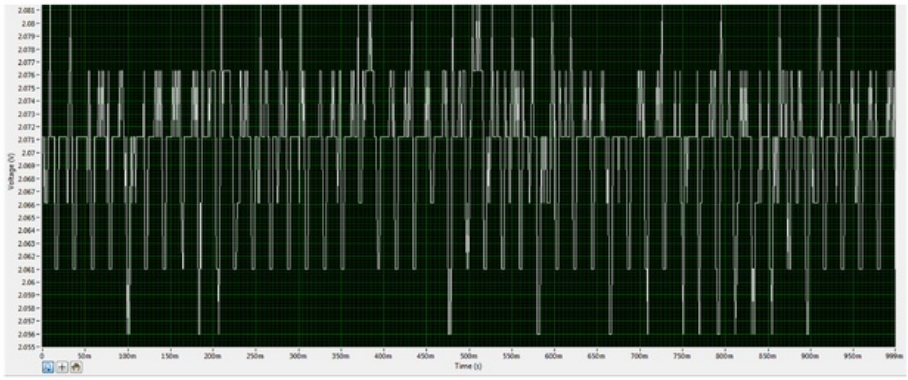


Figure 97 - Laser signal noise on wood target

Laser signal noise on a reflective surface target can be seen in figure 98. The signal of the reflective surface went open circuit and gave mV reading at 2077mm.

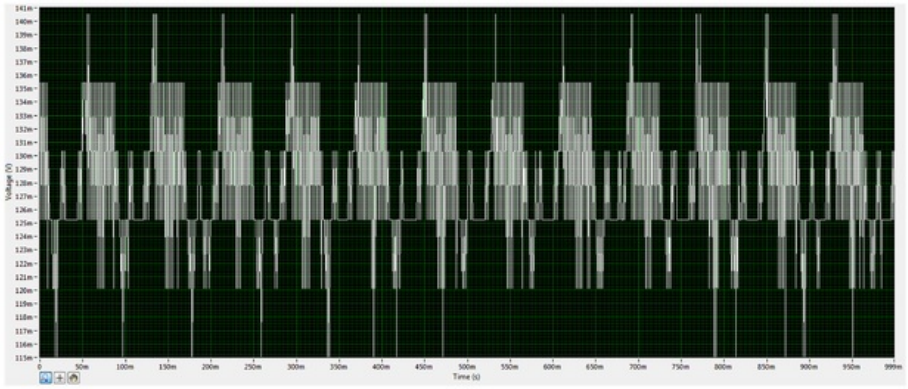


Figure 98 - Laser signal noise on reflective target

This was unexpected as it was assumed that the reflective target would return the best signal for the laser as the research concluded. However the research into phase shift lasers showed that it is possible to introduce too high levels on the rf channel with too large an amplitude of useful signal. This results in clipping and distortion. As the research stated, this could be avoided by either defocussing the photodiode or the target to ensure the receiver reives less light.

Figure 99 shows the signal dropping out when too much light is reflected. This must therefore be considered when commissioning to ensure a target without too much reflectivity is utilised as any intermittent failures could result in incorrect system performance becoming a hazard. This must be considered under further work.

Although this analysis proves the correct operation using wood as a reflector, there was not enough time allocated to continue these tests to find the optimum surface for reflection. This must be conducted under further work.

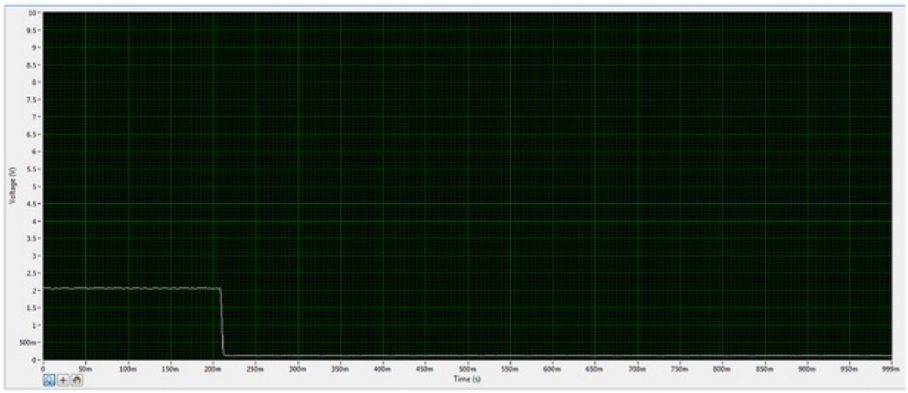


Figure 99 - Laser signal dropping out on reflective surface



Figure 100 - Laser fault "Too much light"

6.2 User Feedback Evaluation

It was deemed highly important that the completed system be critically analysed in order to determine any areas of concern. If this was not carried out it then potential bugs in the system could affect production and crane performance with potential health and safety concerns.

As the two main user groups of the crane system are both operators and engineers, it was decided that the most advantageous feedback of system functionality would have to come in the form of a questionnaire. The two groups were asked to test the system as if they were carrying out their daily tasks and then a questionnaire was issued.

6.2.1 Questionnaire Type

The survey type selected was "semi-supervised". This was so that the researcher (author of the project) could explain the objectives and format of the questionnaire and then allow the subjects to provide the information on their own (35). This was selected over "supervised" and "unsupervised" as it was decided this would be the best way to ensure the subjects gave the most useful feedback.

6.2.2 Survey Objectives

1. To determine the overall effectiveness of the system from both operator and engineer perspective.
2. To obtain reliable feedback from the users as to system performance when conducting their tasks.
3. To determine if any features of the system are problematic and if so, in what way.
4. To obtain feedback on how the system could be improved to benefit the user.

6.2.3 Experimental design

The questionnaire is going to take an experimental design approach as it is assessing the impact of the system rather than describing a phenomenon of interest (36). The experimental design type selected "was a concurrent control study with non-random assignation of participants". This is because the participants of the survey were in two groups, namely engineers and operators, and were treated differently with different question sets.

6.2.4 Sample Size

Due to the nature of the workforce who is coming into contact with the system, the sample size had to be relatively small with just 4 operators and 3 engineers. The sample set selected was deemed to be truly representative of the population intended to survey.

6.2.5 Question Types

It was decided to incorporate the two question types both open and closed questions in the survey with. This was to ensure that the maximum information was retrieved from the questionnaire even though the author was aware open questions are more difficult to analyse. The engineer question set contained more open questions as a more detailed response was required whereas the operator question set could afford to be a more general response.

6.2.6 Questionnaire Analysis

A full breakdown of results can be seen in appendix 3 and 4. With regards to satisfaction of the system items 90% of operators questioned were satisfied or very satisfied compared to 100% of engineers as seen in figures 101 and 102

1. The following is a list of system items. How satisfied are you based on the following criteria?

	Very Dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied	Response Total
Overall quality	0.0% (0)	0.0% (0)	0.0% (0)	25.0% (1)	75.0% (3)	4
Usability	0.0% (0)	0.0% (0)	0.0% (0)	50.0% (2)	50.0% (2)	4
Reliability	0.0% (0)	0.0% (0)	25.0% (1)	50.0% (2)	25.0% (1)	4
Safety	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	100.0% (4)	4
Relativity to task	0.0% (0)	0.0% (0)	25.0% (1)	50.0% (2)	25.0% (1)	4
					answered	4
					skipped	0

Figure 101 - Operator satisfaction of system items

1. The following is a list of system items. How satisfied are you based on the following criteria?

	Very Dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied	Response Total
Overall quality	0.0% (0)	0.0% (0)	0.0% (0)	66.7% (2)	33.3% (1)	3
Usability	0.0% (0)	0.0% (0)	0.0% (0)	66.7% (2)	33.3% (1)	3
Relisability	0.0% (0)	0.0% (0)	0.0% (0)	33.3% (1)	66.7% (2)	3
Safety	0.0% (0)	0.0% (0)	0.0% (0)	33.3% (1)	66.7% (2)	3
Relativity to task	0.0% (0)	0.0% (0)	0.0% (0)	66.7% (2)	33.3% (1)	3
					answered	3
					skipped	0

Figure 102 -Engineer satisfaction of system items

Overall Engineer Satisfaction

$$\frac{1197.22}{1300} \times 100 = 92\%$$

Overall Operator Satisfaction

$$\frac{999.3}{1200} \times 100 = 83\%$$

Total overall Satisfaction

$$\frac{(92 + 83)}{200} \times 100 = 87.5\%$$

6.2.7 Questionnaire Outcome

The comments received from both engineers and operators (all users) provided feedback and an insight into the systems drawbacks and limitations. These are displayed in table 6.

Table 6 - User feedback comments

Engineer Feedback	
Comment	**Analysis**
Although the functionality to change the zones and bay length was very good, the coloured animation bars require manual adjustment when the system is installed. Would be nice if this was adjusted automatically.	As it stands it was the author's intention that the system be initially set up during commissioning. By implementing this improvement the system becomes more flexible and would allow for easy integration to any cranes.
When overriding the system, although the indication of this is suitable, there is no indication on the panel only the HMI. This is not required but would be a nice addition.	This was not deemed necessary as the HMI provides ample indication that an override is initiated. As the HMI is used when driving the crane this was deemed more than adequate.
The alarms page was very helpful when fault finding and provided all the required information as long as the alarms were current! Alarm logging would allow for previous faults to be recorded checking for reoccurring issues.	This would be a good improvement but was not deemed necessary for the project under the current specification.
When driving the crane between zones to set operational distances, sometime a chattering/flickering of warnings and indication would occur. Not an issue but could be improved.	This was not noticed during testing and must be remedied under further work for the project prior to installation on a crane.

Operator Feedback	
Comment	**Analysis**
Although this is a vast improvement to the current situation, there is potential to be working on a crane with multiple cranes operating in the bay. The system does not allow for measurement between cranes.	This was not required under the current project objectives but will be a necessary upgrade to make the system suitable for multiple cranes in a bay.

Give the operators override ability	The objective of the project was to provide security where only engineers can override the system for safety reasons. Although operator may find this annoying, it is a necessity.

6.2.8 Evaluation summary

Overall the feedback received from both the accuracy testing and questionnaires indicate the project has been a success. Whilst there are some limitations to the system as indicated by the comments, these can be addressed, and the overall satisfaction (87.5%) indicates a successfully implemented solution. The questionnaire has also provided some critical feedback into system errors which will be addressed in the further work. The results from the accuracy testing prove that the system is operating to the required standard, providing detailed distance feedback, which is utilised for anti-collision control within set parameters.

Chapter 7 - Conclusion & Recommendations

Due to the continued reports of high bay crane collisions in TATA Steel, this project set out to research and develop a suitable anti-collision distance tracking system which could be presented to higher management as a potential solution to the problem.

With regards to the mandatory aims and design objectives, this project has achieved all that it set out to. A solution to the issue at hand was researched and provided with a suitable laser tested and utilised. A PLC was utilised for control with a HMI providing indication and usability of the system. This was all installed on a purpose built rig for presentation to CAPL engineering managers.

Despite the success of the build, the analysis concluded that contrary to prior belief, a mirror type target does not offer the best signal output from the laser due to clipping and "too much light" being reflected. This was an important finding as it has eliminated the potential for incorrect readings being received from the laser which could potentially effect system performance and more importantly, impact on safety.

With an overall satisfaction of potential users at 87.5% it can be concluded that the system operates to a suitable standard with some limited further work required in order for it to be deemed ready for installation on TATA cranes.

7.1 Further Work & Improvements

Many of the following improvements have been chosen as a result of feedback received from the questionnaire. These have been assessed and deemed as necessary improvements.

7.1.1 Prevent rapid switching of "crane zones"

As indicated by the feedback from the questionnaire, it is required to incorporate measures to prevent this occurring. Introducing interlocked timer contacts in the code when a specific zone is activated will prevent the flickering of indication when the crane is on the limit between zones. This could be done by activating an on delay timer when a particular zone is triggered and placing a contact in each of the ladder rungs activating the other two zones. This would prevent the other zones becoming activated until the current zone has been

active for a set period of time, 2 seconds for example. This will prevent any erratic flickering between zones.

7.1.2 Automatic adjustment of bay zones graphic

Currently the healthy, warning and trip zone graphic on the HMI requires initial set up during commissioning. Although this is not an issue, by incorporating a means of automatic scaling of the zones graphic, the animation on the HMI will update in relation to the allocated distance of the bay. This would allow easy integration of the system into any length bay with ease and not require manual adjustment.

7.1.3 Alarm logging

As retrieved from the questionnaire feedback, a logging of alarms would provide better understanding of system performance and a history of crane operation. This would aid the engineers in determining why certain fault may be occurring more frequently and provide a platform on which more effective fault finding and system analysis could be carried out. This can be done using the alarms logging function in TIA Portal which allows all activated alarms to be logged and exported to an external storage device.

7.1.4 Dual laser control

The system currently obtains a distance reading from the East wall only and determines the distance to the West wall based on the length of bay set in the HMI. With the introduction of a secondary laser mounted the opposite direction, the system can be improved to provide exact distance reading of the crane to obstacles in both directions. This would have to be utilised should the system be required for crane to crane anti-collision.

7.1.5 Speed control of crane

Currently, the system provides indication of crane location and a trip function by dropping out the healthy interlock of the crane. Further work which will be carried out on the system will be utilising the MOXA switch (already installed) to provide direct control of the crane speed DDC Drives. As these are on a serial network the MOXA will allow the S7-1200 control of these drives.

It is intended that when the crane is in the healthy zone, full speed can be applied. However when the warning zone is activated, a slowdown signal reference would be sent to the drives

preventing the crane inertia from carrying it through the trip zone. This is particularly important for crane to crane anti-collision as there is the potential of having both cranes travelling at full speed towards each other. See figure 103.

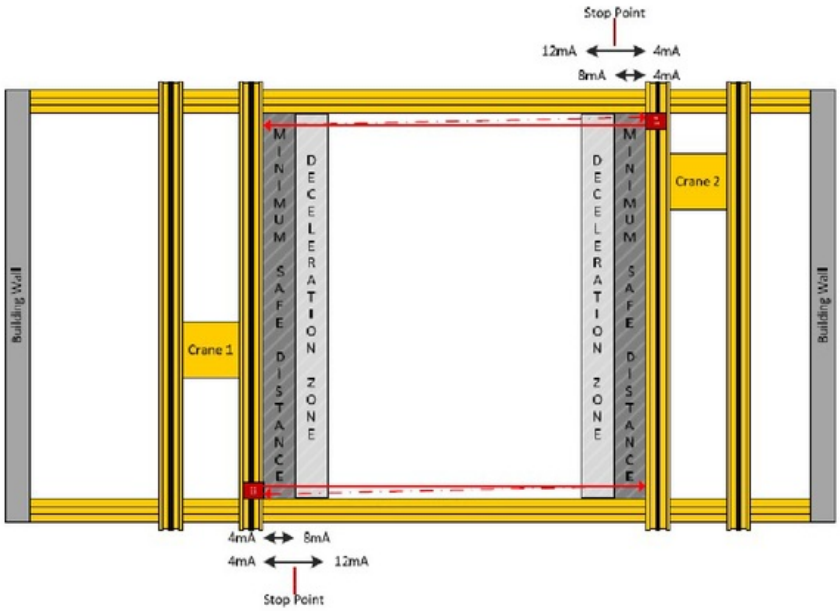


Figure 103 - Crane Speed Control (27)

7.1.6 Testing of materials to ensure optimum target utilised

As the analysis of laser signal output on some different surfaces proved reflective targets pose issues, it has been decided that it is necessary to continue these tests on a range of target materials to ensure the optimum signal is received (least noise and accurate). Currently, a wooden surface gave the best results with the least noise on the signal however it is believed that this could be further improved.

7.1.7 Signal Intermittency

As the testing on a reflective target concluded, it is possible for the laser signal to give intermittent readings under certain conditions. This poses the question, what about signal overshoot or temporary blips due to varying conditions on site? It is intended to provide a means where the system will ignore any temporary blips in the signal. This could be done by utilising and off delay timer whereby the signal must drop out for a set time, 2 seconds for example before the off delay timer contact will give the trip output.

7.2 Reflection

In order to develop a suitable solution to the problem in hand I first had to conduct research into what was currently on the market and what technology would best suit the application. This took up a vast amount of my time as I underestimated how in depth I would be required to go in order to find the correct solution. As I felt overwhelmed by the vast amount of work required, I believe this hindered my progress in the early stages as I did not think rationally and prioritise my time correctly from the outset. This could have thrown the whole project however I quickly recognised the wrong course I was on and made an active effort to correct it which resulted the projected getting back on schedule and finishing on time. From this I have learned to prioritise my time on every aspect of a project as there is no time like the present to do something. This is an outlook I will strive to maintain for the rest of my career.

As the project relied heavily on using a PLC for control and programming designing the HMI interface, I was required to gain good understanding of how best to develop a program in keeping with industry practice. This was another aspect of the project I completely underestimated as I believed I had good enough knowledge of PLCs in order to undertake the task. It quickly became apparent that I had nowhere near the knowledge required in order to complete the objectives and a vast amount of further work would have to be carried out in the background. Initially I felt although I did not have the ability to complete the project and felt overwhelmed by the task, perhaps because I felt out of my depth as I only had a basic knowledge of PLCs. With the support of my workplace, and after a few months struggle, I approached my managers and requested I be sent on a training course. Although this incurred a substantial cost to the company, and much effort on my part (5 days away from home in Manchester), the course challenged me but gave me the confidence and knowledge I needed to continue my project. This has taught me that it is not worth struggling alone, and to ask for help if required. If I had done this sooner, I would not have wasted time at a dead end and gotten past the hurdle sooner. I need to ensure I continue to maintain that outlook and never be embarrassed to admit help is needed.

Overall I am incredibly proud of the final outcome of the project and feel I have progressed as an engineer. This project has been one of the most challenging experiences I have encountered to date however I have met all the objectives and more. Management are extremely happy with the result and have expressed their desire for me to continue my work

improving the system and installing it with the greater goal of potentially eliminating the potential for any further accidents.

Bibliography

1. http://www.fast.u-psud.fr/~martin/acoustique/support/r%C3%A9flection-r%C3%A9fraction.pdf
2. http://www.ndt.net/article/ecndt02/254/254.htm
3. http://documents.irevues.inist.fr/bitstream/handle/2042/2330/017.PDF+TEXTE.pdf?sequence=3
   http://www.ab.com/en/epub/catalogs/12772/6543185/12041221/12041229/print.html
4. http://www.utdallas.edu/~aiken/LASERCLASS/laserprinlipels.pdf
5. https://www.rp-photonics.com/phase_shift_method_for_distance_measurements.html
6. https://www.researchgate.net/publication/228351511_Comparison_of_TOF_FMCW_and_Phase-Shift_Laser_Range-Finding_Methods_by_Simulation_and_Measurement
7. file:///C:/Users/Owner/Downloads/JCIS06-PNC-38.pdf - file:///C:/Users/Owner/Downloads/ISMTII-1-53.pdf -
8. http://pe2bz.philpem.me.uk/Lights/-%20Laser/Info-999-LaserCourse/C00-M06-LaserDistanceMeasurement/module6.htm - http://www.wseas.us/e-library/conferences/2006cavtat/papers/523-107.pdf
9. file:///C:/Users/Owner/Downloads/sensors-15-16153.pdf
   http://www.laser-distance-measurer.com/accuracy-and-ultrasonic-distance

11. meter/#.VsNsPfKLSUk –
12. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20080026181.pdf
13. https://pure.ltu.se/portal/files/129215/LTU-DT-0443-SE.pdf -
14. http://www.gigasense.se/wp-content/uploads/2013/03/0810-1_bro_Gigasense_Anti-Coll_en_131024_Web.pdf
15. https://www.ergonomicpartners.com/pdf/magnetek-laserguard-crane-collision-avoidance-system-brochure.pdf
16. http://www.ni.com/newsletter/50262/en/
17. https://www.siemens.ca/web/portal/en/ProductsServices/Documents/SummerSpecial/S7-1200%20CPU%20Touch%20Panel.pdf

Works Cited

1. **Bhattacharya, S K.** *Control of Electrical Machines.* s.l. : New Age International, 2003.

2. **Brauer, Roger L.** *Safety and Health for Engineers.* s.l. : Wiley-Blackwell, 2006.

3. sensors february march 1999. *massa.com.* [Online] Februrary 1999. [Cited: 20 06 2015.] http://www.massa.com/wp-content/uploads/Sensors_February-March_1999.pdf.

4. Sonar principles. *wikipedia.com.* [Online] [Cited: 20 06 2015.] https://en.wikipedia.org/wiki/Ultrasound#/media/File:Sonar_Principle_EN.svg.

5. **Leopoldo Angrisani, Aldo Baccigalupi and Rosario Schiano Lo Moriello.** *Kalman Filter Recent Advances and Applications.* s.l. : InTech, 2009.

6. **freescale semiconductor.** Ultrasonic distance measurer. *home.zhaw.ch.* [Online] 2008. [Cited: 20 06 2015.] https://home.zhaw.ch/kunr/ETP/ETP2011/AN3481.pdf.

7. **Beranek, Leo L.** Acoustic Properties of Gasses. *American Institute of Physics Handbook.* s.l. : McGraw-Hill, 1972.

8. Ultrasonic sensing. *www.ab.com.* [Online] [Cited: 13 08 2015.] http://www.ab.com/en/epub/catalogs/12772/6543185/12041221/12041229/print.html.

9. fundamentals of photoelectric sensors. *www.automation.com.* [Online] [Cited: 16 12 2015.] http://www.automation.com/library/articles-white-papers/sensors-sensing-technologies/fundamentals-of-photoelectric-sensors.

10. Distance measurement with lasers. *www.rp-photonics.com.* [Online] [Cited: 16 07 2015.] https://www.rp-photonics.com/distance_measurements_with_lasers.html.

11. **al, Amann et.** *Laser ranging: a critical review of usual techniques.* s.l. : Optical Engineering, 2001. Vol. 40 No. 1.

12. **Kipela, Ari.** *Pulsed TOF laser range finder techniques for fast, high precision measurement applications.* s.l. : Department of Electrical and Information Engineering, University of Oulu, 2004.

13. Module 6 Laser Distance Measurement. *www.pe2bz.philpem.me.uk/.* [Online] [Cited: 10 12 2015.] http://pe2bz.philpem.me.uk/Lights/-%20Laser/Info-999-LaserCourse/C00-M06-LaserDistanceMeasurement/module6.htm.

14. *Phase-shift laser range finder based on highspeed and high precision phase-measuring techniques.* **Pengcheng Hu1, #, Jiubin Tan1, Hongxing Yang1, Xiping Zhao1 and Siyuan Liu2.** x, s.l. : THE 10th INTERNATIONAL SYMPOSIUM OF MEASUREMENT TECHNOLOGY AND INTELLIGENT INSTRUMENTS, 2011, Vol. x.

15. *Comparison of TOF, FMCW and Phase-Shift Laser Range-Finding Methods by Simulation and Measurement.* **Nejad, Shahram Mohammad.** 1, s.l. : Quartarly Journal of Technology & Education, 2006, Vol. 1.

16. MODULE 6LASER DISTANCE MEASUREMENT. [Online] [Cited: 20 12 15.] http://pe2bz.philpem.me.uk/Lights/-%20Laser/Info-999-LaserCourse/C00-M06-LaserDistanceMeasurement/module6.htm.

17. **Nejad, Shahram Mohammad.** *A new design of laser phase-shift range finderindependent of environmental conditions and thermal drift.*

18. **S. Reza, R. Ricken, V. Quiring, and W. Sohler.** *High Resolution Optical Frequency Domain Ranging with an Integrated Frequency Shifted Feedback (FSF) Laser.* s.l. : IEEE Xplore, 2007. paper cj3-5-THU.

19. *Phase noise limited resolution of coherent LIDAR using widely tunable laser diodes.* **Amann, M-C.** 18, s.l. : Electronics Letters, 1992, Vol. 28.

20. **Monsi, Mohammad Sohrab Hossan.** *Laser Radar for Precise Vegicle Velocity Measurement.* s.l. : Deutchse Nationalbibliothek, 2009.

21. Accuracy and Ultrasonic Distance meters. *www.laser-distance-measurer.com.* [Online] [Cited: 6 11 2015.] http://www.laser-distance-measurer.com/accuracy-and-ultrasonic-distance-meter/#.VsW8x_KLSUl.

22. **Sentek solutions.** *KAD 300 series PDF.* 2016.

23. **CATRON group international.** *LCAS CATRON laser collision avoidance system PDF.* [2016]

24. laserguard 2. *www.magnatekmh.com.* [Online] [Cited: 10 01 2016.] http://www.magnetekmh.com/products/collision%20avoidance%20systems/collision%20avoidance/laserguard2.

25. **gigasense.** Anti collision. *www.gigasense.se.* [Online] [Cited: 12 01 2016.] http://www.gigasense.se/product/anti-collision/.

26. **TR Electronic.** *Overhead Gantry Crane Collision Avoidance.* 2016.

27. **Siemens.** *Power Supply S7-1200.* [Data Sheet] 2016. 6EP1332-1SH71.

28. SM1221 DI. *Siemens.com.* [Online] [Cited: 6 01 2016.] https://mall.industry.siemens.com/mall/en/WW/Catalog/Product/6ES7221-1BF32-0XB0.

29. www.sensorsincorporated.com. *Sick DME 200 Laser.* [Online] [Cited: 24 02 2016.] http://www.sensorsincorporated.com/uploaded/Doc/DME%202000%20Product%20Info.pdf.

30. www.sick.com. *sick DME 400.* [Online] [Cited: 24 02 2016.] https://www.sick.com/de/en/distance-sensors/long-range-distance-sensors/dme4000/dme4000-112/p/p204046.

31. 01d100. *www.ifm.com.* [Online] [Cited: 24 02 2016.] http://www.ifm.com/products/gb/ds/O1D100.htm.

32. NPort 5410/NPort 5430/NPort 5450 Series. *www.moxa.com.* [Online] [Cited: 25 02 2016.] http://www.moxa.com/product/NPort_5410.htm.

33. **Siemens.** Delivery release of Field PG 4. *Siemens.com.* [Online] [Cited: 15 03 2016.] https://support.industry.siemens.com/cs/document/67329030/delivery-release-for-field-pg-m4?dti=0&lc=en-DE.

34. **Health and Saftey Executive.** Safe Use of Work Equipment. *www.hseni.go.uk.* [Online] 2014. [Cited: 03 03 2016.] http://www.hseni.gov.uk/l22_safe_use_of_work_equipment.pdf.

35. **UWTSD Swansea.** *Survey Design Lecture 13.* [Powerpoint] Researc & Development methods : s.n.

36. *Principles of Survey Research Part 2: Designing a Survey.* **Kitchenham, Barbara A.** 1, s.l. : ACM SIGSOFT, January 2002, Vol. 27.

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Appendix 1 – Operator Evaluation of Crane Tracking System

1. The following is a list of system items. How satisfied are you based on the following criteria?

	Very Dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied
Overall quality	☐	☐	☐	☐	☐
Usability	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐
Relativity to task	☐	☐	☐	☐	☐

2. In comparison between no safety control and the new system, would you say overall crane safety has

- ☐ Drastically improved
- ☐ Somewhat improved
- ☐ Stayed the same

3. When using the system, do you think it would impede your daily tasks?

- ○ Yes
- ○ No

if yes, in what way?

4. Which of the following best describes the accuracy of the system in relation to crane location in the bay?

- ☐ Extremely accurate
- ☐ Very Accurate
- ☐ Somewhat accurate
- ☐ Not very accurate
- ☐ Very unaccurate

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5. Which of the following best describes the system usability

- [ ] Extremely user friendly
- [ ] Very user friendly
- [ ] Somewhat user friendly
- [ ] Not very user friendly

6. On a scale of 1-10 how effective do you think this system will be in preventing any further crane collisions

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5
- [ ] 6
- [ ] 7
- [ ] 8
- [ ] 9
- [ ] 10

7. Are there any features of the system you would improve, and if so, please specify.

- [ ] Yes
- [ ] No

Comments:

8. Are there any features of the system you think worked particularly well?

- ( ) Yes
- ( ) No

Please Specify

Previous Page | Finish Survey

Appendix 2 – Engineer Evaluation of Crane Tracking System

1. The following is a list of system items. How satisfied are you based on the following criteria?

	Very Dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied
Overall quality	☐	☐	☐	☐	☐
Usability	☐	☐	☐	☐	☐
Reliability	☐	☐	☐	☐	☐
Safety	☐	☐	☐	☐	☐
Relativity to task	☐	☐	☐	☐	☐

2. In comparison between no safety control and the new system, would you say overall crane safety has

- ☐ Drastically improved
- ☐ Somewhat improved
- ☐ Stayed the same

3. How did you find the alarm functionality when fault finding?

- ☐ Extremely informative
- ☐ Very informative
- ☐ Somewhat informative
- ☐ Not Very informative

4. When commissioning the system, how satisfied were you with the systems ability to adapt?

- ☐ Very Dissatisfied
- ☐ Dissatisfied
- ☐ Neutral
- ☐ Satisfied
- ☐ Very Satisfied

If you feel there are any improvements that are required, please specify here

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5. Which of the following best describes the accuracy of the system in relation to crane location in the bay?

- [ ] Extremely accurate
- [ ] Very Accurate
- [ ] Somewhat accurate
- [ ] Not very accurate
- [ ] Very unaccurate

6. Which of the following best describes the system usability

- [ ] Extremely user friendly
- [ ] Very user friendly
- [ ] Somewhat user friendly
- [ ] Not very user friendly

7. On a scale of 1-10 how effective do you think this system will be in preventing any further crane collisions

- [ ] 1
- [ ] 2
- [ ] 3
- [ ] 4
- [ ] 5
- [ ] 6
- [ ] 7
- [ ] 8
- [ ] 9
- [ ] 10

8. Are there any features of the system you would improve, and if so, please specify.

- [ ] Yes
- [ ] No

Comments:

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9. Are there any features of the system you think worked particularly well?

- ○ Yes
- ○ No

Please Specify

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Appendix 3 - Engineer Evaluation of Crane Tracking System

1. The following is a list of system items. How satisfied are you based on the following criteria?						
	Very Dissatisfied	**Dissatisfied**	**Neutral**	**Satisfied**	**Very Satisfied**	**Response Total**
Overall quality	0.0% (0)	0.0% (0)	0.0% (0)	66.7% (2)	33.3% (1)	3
Usability	0.0% (0)	0.0% (0)	0.0% (0)	66.7% (2)	33.3% (1)	3
Reliability	0.0% (0)	0.0% (0)	0.0% (0)	33.3% (1)	66.7% (2)	3
Safety	0.0% (0)	0.0% (0)	0.0% (0)	33.3% (1)	66.7% (2)	3
Relativity to task	0.0% (0)	0.0% (0)	0.0% (0)	66.7% (2)	33.3% (1)	3
					answered	3
					skipped	0

Matrix Charts

1.1. Overall quality								**Response Percent**	**Response Total**
1	Very Dissatisfied							0.0%	0
2	Dissatisfied							0.0%	0
3	Neutral							0.0%	0
4	Satisfied							66.7%	2
5	Very Satisfied							33.3%	1
Analysis	Mean:	4.33	Std. Deviation:	0.47	Satisfaction Rate:	83.33		answered	3
	Variance:	0.22	Std. Error:	0.27					

1.2. Usability			Response Percent	Response Total
1	Very Dissatisfied		0.0%	0
2	Dissatisfied		0.0%	0
3	Neutral		0.0%	0
4	Satisfied		66.7%	2
5	Very Satisfied		33.3%	1
Analysis	Mean: 4.33 Std. Deviation: 0.47 Satisfaction Rate: 83.33 Variance: 0.22 Std. Error: 0.27		answered	3

1.3. Reliability			Response Percent	Response Total
1	Very Dissatisfied		0.0%	0
2	Dissatisfied		0.0%	0
3	Neutral		0.0%	0
4	Satisfied		33.3%	1
5	Very Satisfied		66.7%	2
Analysis	Mean: 4.67 Std. Deviation: 0.47 Satisfaction Rate: 91.67 Variance: 0.22 Std. Error: 0.27		answered	3

1.4. Safety			Response Percent	Response Total
1	Very Dissatisfied		0.0%	0
2	Dissatisfied		0.0%	0
3	Neutral		0.0%	0
4	Satisfied		33.3%	1
5	Very Satisfied		66.7%	2
Analysis	Mean: 4.67 Std. Deviation: 0.47 Satisfaction Rate: 91.67 Variance: 0.22 Std. Error: 0.27		answered	3

1.5. Relativity to task			Response Percent	Response Total
1	Very Dissatisfied		0.0%	0
2	Dissatisfied		0.0%	0
3	Neutral		0.0%	0
4	Satisfied		66.7%	2
5	Very Satisfied		33.3%	1
Analysis	Mean: 4.33 Std. Deviation: 0.47 Satisfaction Rate: 83.33 Variance: 0.22 Std. Error: 0.27		answered	3

2. In comparison between no safety control and the new system, would you say overall crane safety has

		Response Percent	Response Total
1	Drastically improved	100.00%	3
2	Somewhat improved	0.00%	0
3	Stayed the same	0.00%	0

Analysis							answered	3
	Mean:	0	Std. Deviation:	0	Satisfaction Rate:	100	skipped	0
	Variance:	0	Std. Error:	0				

3. How did you find the alarm functionality when fault finding?

		Response Percent	Response Total
1	Extremely informative	66.67%	2
2	Very informative	33.33%	1
3	Somewhat informative	0.00%	0
4	Not Very informative	0.00%	0

Analysis							answered	3
	Mean:		Std. Deviation:		Satisfaction Rate:	91.67	skipped	0
	Variance:		Std. Error:					

4. When commissioning the system, how satisfied were you with the system's ability to adapt?

		Response Percent	Response Total
1	Very Dissatisfied	0.00%	0
2	Dissatisfied	0.00%	0
3	Neutral	33.33%	1
4	Satisfied	0.00%	0
5	Very Satisfied	66.67%	2

Analysis							answered	3
	Mean:	4.33	Std. Deviation:	0.94	Satisfaction Rate:	83.33	skipped	0
	Variance:	0.89	Std. Error:	0.54				

If you feel there are any improvements that are required, please specify here (1)

1	Although the functionality to change the zones and bay length was very good, the coloured animation bars require manual adjustment when the system is installed. Would be nice if this was adjusted automatically.

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5. Which of the following best describes the accuracy of the system in relation to crane location in the bay?

		Response Percent	Response Total
1	Extremely accurate	100.00%	3
2	Very Accurate	0.00%	0
3	Somewhat accurate	0.00%	0
4	Not very accurate	0.00%	0
5	Very inaccurate	0.00%	0

Analysis							
	Mean:	0	Std. Deviation:	0	Satisfaction Rate:	100	
	Variance:	0	Std. Error:	0			

answered	3
skipped	0

6. Which of the following best describes the system usability

		Response Percent	Response Total
1	Extremely user friendly	100.00%	3
2	Very user friendly	0.00%	0
3	Somewhat user friendly	0.00%	0
4	Not very user friendly	0.00%	0

Analysis							
	Mean:	1	Std. Deviation:	0	Satisfaction Rate:	100	
	Variance:	0	Std. Error:	0			

answered	3
skipped	0

7. On a scale of 1-10 how effective do you think this system will be in preventing any further crane collisions

		Response Percent	Response Total
1	1	0.00%	0
2	2	0.00%	0
3	3	0.00%	0
4	4	0.00%	0
5	5	0.00%	0
6	6	0.00%	0
7	7	0.00%	0
8	8	33.33%	1
9	9	33.33%	1
10	10	33.33%	1

Analysis							
	Mean:	9	Std. Deviation:	0.82	Satisfaction Rate:	88.89	
	Variance:	0.67	Std. Error:	0.47			

answered	3
skipped	0

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8. Are there any features of the system you would improve, and if so, please specify?

		Response Percent	Response Total
1	Yes	100.00%	3
2	No	0.00%	0

Analysis							answered	3
	Mean:	0	Std. Deviation:	0	Satisfaction Rate:	100		
	Variance:	0	Std. Error:	0			skipped	0

Comments: (3)

1		When overriding the system, although the indication of this is suitable, there is no indication on the panel only the HMI. this is not required but would be nice addition.
2		The alarms page was very helpful when fault finding and provided all the required information as long as the alarms were current! Alarm logging would allow for previous faults to be recorded checking for reoccurring issues.
3		when setting the crane between zones to set operational distances, sometime a chattering/flickering of warnings and indication would occur. Not an issue but could be improved.

9. Are there any features of the system you think worked particularly well?

		Response Percent	Response Total
1	Yes	100.00%	3
2	No	0.00%	0

Analysis							answered	3
	Mean:	0	Std. Deviation:	0	Satisfaction Rate:	100		
	Variance:	0	Std. Error:	0			skipped	0

Please Specify (3)

1		The alarms page provided very useful feedback to aid fault finding in alarm conditions. All current alarms are displayed which is useful.
2		The engineer override and distance control was password protected which is very good. this will prevent operators tampering with a safety system as they definitely would if they could.
3		Everything. the system is a critical improvement which the steelworks has been waiting for.

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Appendix 4 - Operator Evaluation of Crane Tracking System

1. The following is a list of system items. How satisfied are you based on the following criteria?						
	Very Dissatisfied	Dissatisfied	Neutral	Satisfied	Very Satisfied	Response Total
Overall quality	0.0% (0)	0.0% (0)	0.0% (0)	25.0% (1)	75.0% (3)	4
Usability	0.0% (0)	0.0% (0)	0.0% (0)	50.0% (2)	50.0% (2)	4
Reliability	0.0% (0)	0.0% (0)	25.0% (1)	50.0% (2)	25.0% (1)	4
Safety	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	100.0% (4)	4
Relativity to task	0.0% (0)	0.0% (0)	25.0% (1)	50.0% (2)	25.0% (1)	4
					answered	4
					skipped	0

Matrix Charts

1.1. Overall quality			Response Percent	Response Total
1	Very Dissatisfied		0.0%	0
2	Dissatisfied		0.0%	0
3	Neutral		0.0%	0
4	Satisfied		25.0%	1
5	Very Satisfied		75.0%	3
Analysis	Mean: 4.75	Std. Deviation: 0.43	Satisfaction Rate: 93.75	answered 4
	Variance: 0.19	Std. Error: 0.22		

1.2. Usability			Response Percent	Response Total
1	Very Dissatisfied		0.0%	0
2	Dissatisfied		0.0%	0
3	Neutral		0.0%	0
4	Satisfied		50.0%	2
5	Very Satisfied		50.0%	2
Analysis	Mean: 4.5	Std. Deviation: 0.5	Satisfaction Rate: 87.5	answered 4
	Variance: 0.25	Std. Error: 0.25		

1.3. Reliability			Response Percent	Response Total
1	Very Dissatisfied		0.0%	0
2	Dissatisfied		0.0%	0
3	Neutral		25.0%	1
4	Satisfied		50.0%	2
5	Very Satisfied		25.0%	1
Analysis	Mean: 4	Std. Deviation: 0.71	Satisfaction Rate: 75	answered 4
	Variance: 0.5	Std. Error: 0.35		

1.4. Safety			Response Percent	Response Total
1	Very Dissatisfied		0.0%	0
2	Dissatisfied		0.0%	0
3	Neutral		0.0%	0
4	Satisfied		0.0%	0
5	Very Satisfied		100.0%	4
Analysis	Mean: 5	Std. Deviation: 0	Satisfaction Rate: 100	answered 4
	Variance: 0	Std. Error: 0		

1.5. Relativity to task			Response Percent	Response Total
1	Very Dissatisfied		0.0%	0
2	Dissatisfied		0.0%	0
3	Neutral		25.0%	1
4	Satisfied		50.0%	2
5	Very Satisfied		25.0%	1
Analysis	Mean: 4	Std. Deviation: 0.71	Satisfaction Rate: 75	answered 4
	Variance: 0.5	Std. Error: 0.35		

2. In comparison between no safety control and the new system, would you say overall crane safety has

		Response Percent	Response Total
1	Drastically improved	75.00%	3
2	Somewhat improved	25.00%	1
3	Stayed the same	0.00%	0
Analysis	Mean: 0 Std. Deviation: 0 Satisfaction Rate: 87.5	answered	4
	Variance: 0 Std. Error: 0	skipped	0

3. When using the system, do you think it would impede your daily tasks?

		Response Percent	Response Total
1	Yes	25.00%	1
2	No	75.00%	3
Analysis	Mean: 1.75 Std. Deviation: 0.43 Satisfaction Rate: 75	answered	4
	Variance: 0.19 Std. Error: 0.22	skipped	0

if yes, in what way? (1)

1	If I accidentally enter the trip zone on a night shift and the engineer is not available, I would have to wait for him to override the system.

4. Which of the following best describes the accuracy of the system in relation to crane location in the bay?

		Response Percent	Response Total
1	Extremely accurate	50.00%	2
2	Very Accurate	50.00%	2
3	Somewhat accurate	0.00%	0
4	Not very accurate	0.00%	0
5	Very inaccurate	0.00%	0
Analysis	Mean: 0 Std. Deviation: 0 Satisfaction Rate: 83.33	answered	4
	Variance: 0 Std. Error: 0	skipped	0

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5. Which of the following best describes the system usability

		Response Percent	Response Total
1	Extremely user friendly	50.00%	2
2	Very user friendly	50.00%	2
3	Somewhat user friendly	0.00%	0
4	Not very user friendly	0.00%	0

Analysis							answered	4
	Mean:	0	Std. Deviation:	0	Satisfaction Rate:	83.33	skipped	0
	Variance:	0	Std. Error:	0				

6. On a scale of 1-10 how effective do you think this system will be in preventing any further crane collisions

		Response Percent	Response Total
1	1	0.00%	0
2	2	0.00%	0
3	3	0.00%	0
4	4	0.00%	0
5	5	0.00%	0
6	6	0.00%	0
7	7	0.00%	0
8	8	25.00%	1
9	9	50.00%	2
10	10	25.00%	1

Analysis							answered	4
	Mean:	9	Std. Deviation:	0.71	Satisfaction Rate:	88.89	skipped	0
	Variance:	0.5	Std. Error:	0.35				

7. Are there any features of the system you would improve, and if so, please specify.

		Response Percent	Response Total
1	Yes	50.00%	2
2	No	50.00%	2

Analysis							answered	4
	Mean:	1.5	Std. Deviation:	0.5	Satisfaction Rate:	50	skipped	0
	Variance:	0.25	Std. Error:	0.25				

Comments: (2)

1		Give the operators override ability
2		although this is a vast improvement to the current situation, there is potential to be working on a crane with multiple cranes operating in the bay. The system does not allow for measurement between cranes.

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8. Are there any features of the system you think worked particularly well?

			Response Percent	Response Total
1	Yes		100.00 %	4
2	No		0.00%	0

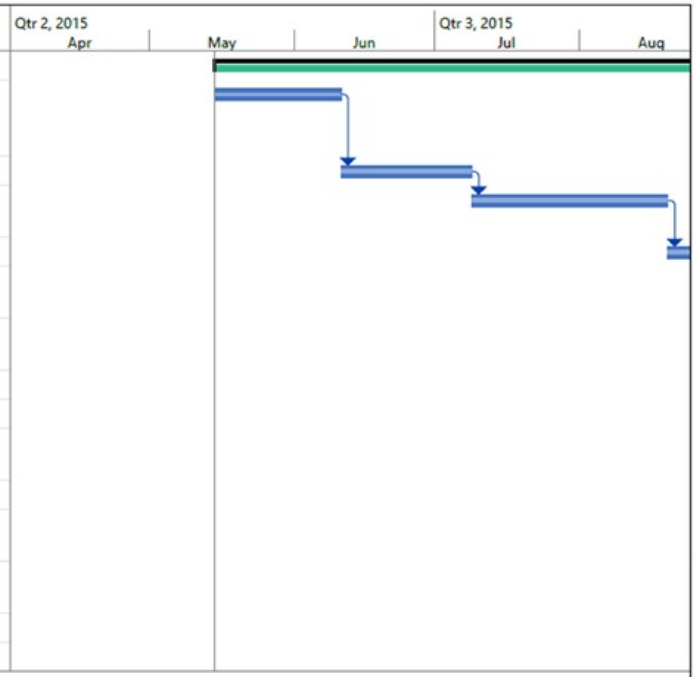
Analysis							
	Mean:	0	Std. Deviation:	0	Satisfaction Rate:	100	answered 4
	Variance:	0	Std. Error:	0			skipped 0

Please Specify (4)

1		Provided very good visual crane location feedback which I have never had before
2		Accurate distance measurement provides useful information for when I can't see the end of the bay very well.
3		The warning indication when entering the warning zone is very useful along with the visual representation and alarms.
4		whole interface is well assembled and provides useful information which will definitely improve safety. The trip conditions are a much needed improvement as this should prevent any further collisions

Appendix 5 - Project Gantt chart

ID	Task Mode	Task Name	Duration	Start	Finish
1		**Research**	**107 days**	**Fri 15/05/15**	**Mon 12/10/15**
2		Current situation & effects of crane downtime	19 days	Fri 15/05/15	Wed 10/06/15
3		Market research	20 days	Thu 11/06/15	Wed 08/07/15
4		Laser Theory	30 days	Thu 09/07/15	Wed 19/08/15
5		PLC theory	31 days	Thu 20/08/15	Thu 01/10/15
6		Communication protocol research	7 days	Fri 02/10/15	Mon 12/10/15
7		**Hardware selection Process**	**49 days**	**Tue 13/10/15**	**Fri 18/12/15**
8		Laser selection	21 days	Tue 13/10/15	Tue 10/11/15
9		PLC selection	13 days	Wed 11/11/15	Fri 27/11/15
10		Other required hardware selection	15 days	Mon 30/11/15	Fri 18/12/15
11		**Installation & Testing**	**65 days**	**Mon 21/12/15**	**Fri 18/03/16**
12		Purchase required hardware	10 days	Mon 21/12/15	Fri 01/01/16
13		Test laser to ensure correct for task	11 days	Mon 04/01/16	Mon 18/01/16
14		Install hardware	15 days	Tue 19/01/16	Mon 08/02/16
15		Write code	19 days	Tue 09/02/16	Fri 04/03/16



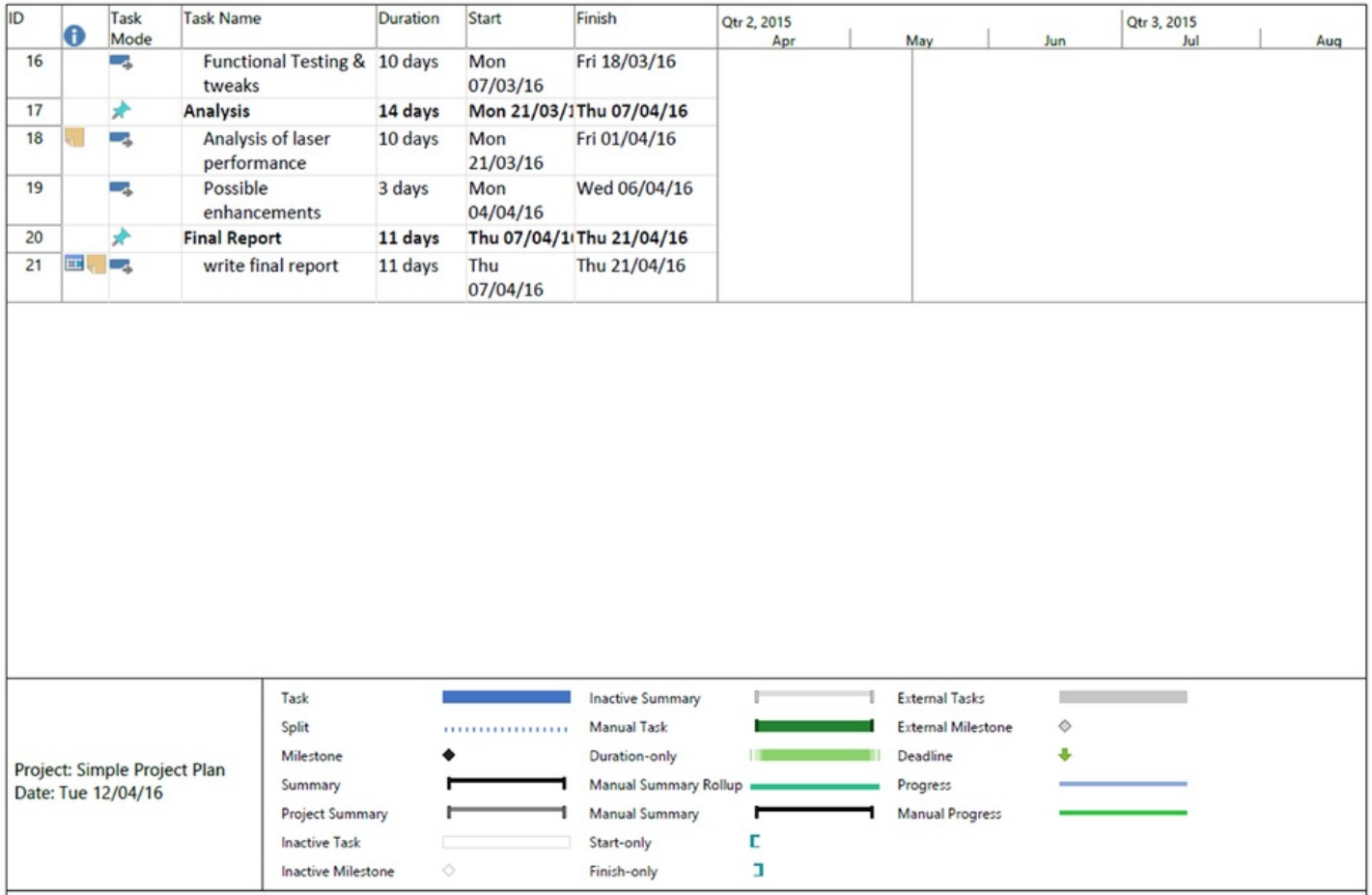
Project: Simple Project Plan
Date: Tue 12/04/16

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Split
Milestone
Summary
Project Summary
Inactive Task
Inactive Milestone
Inactive Summary
Manual Task
Duration-only
Manual Summary Rollup
Manual Summary
Start-only
Finish-only
External Tasks
External Milestone
Deadline
Progress
Manual Progress

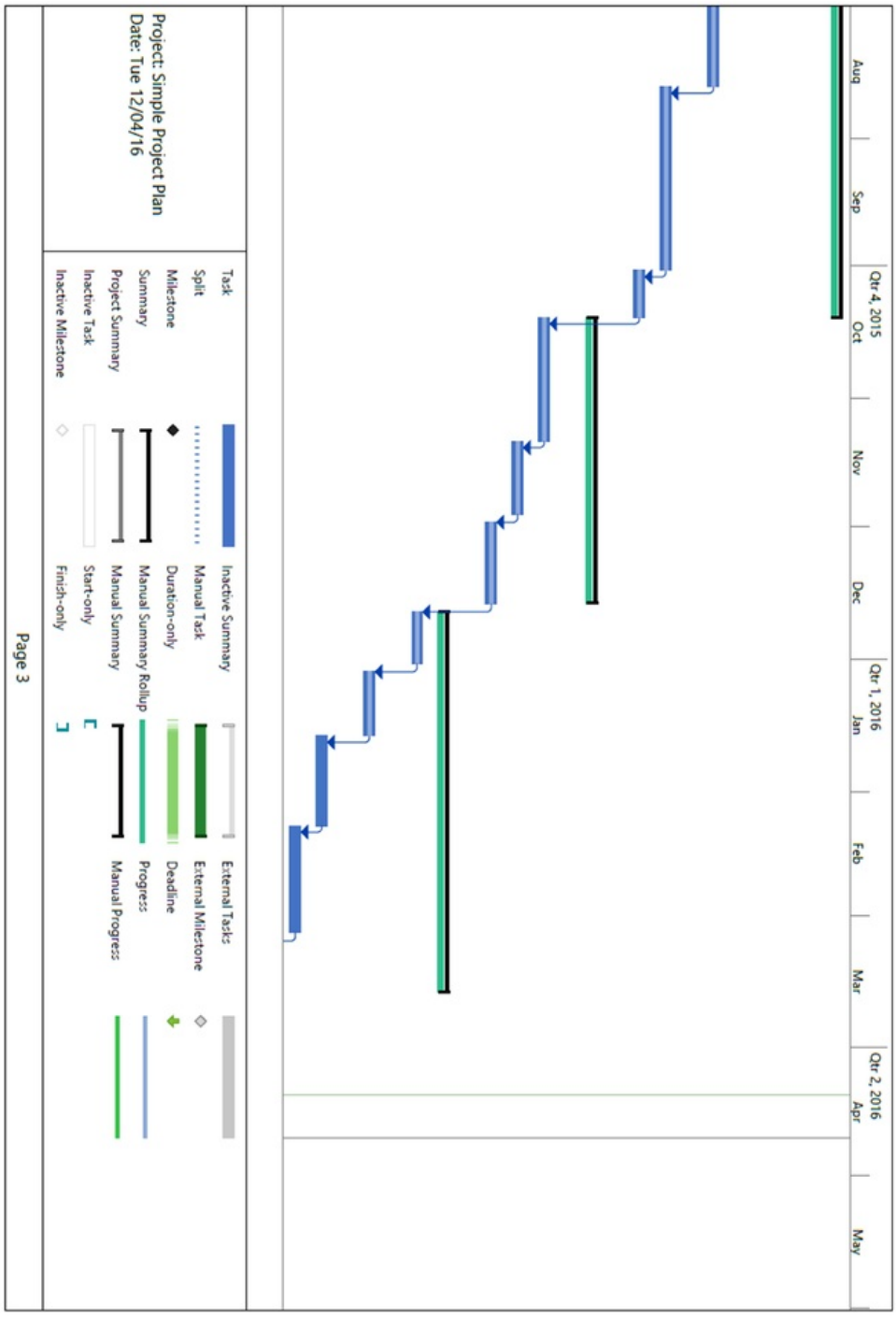
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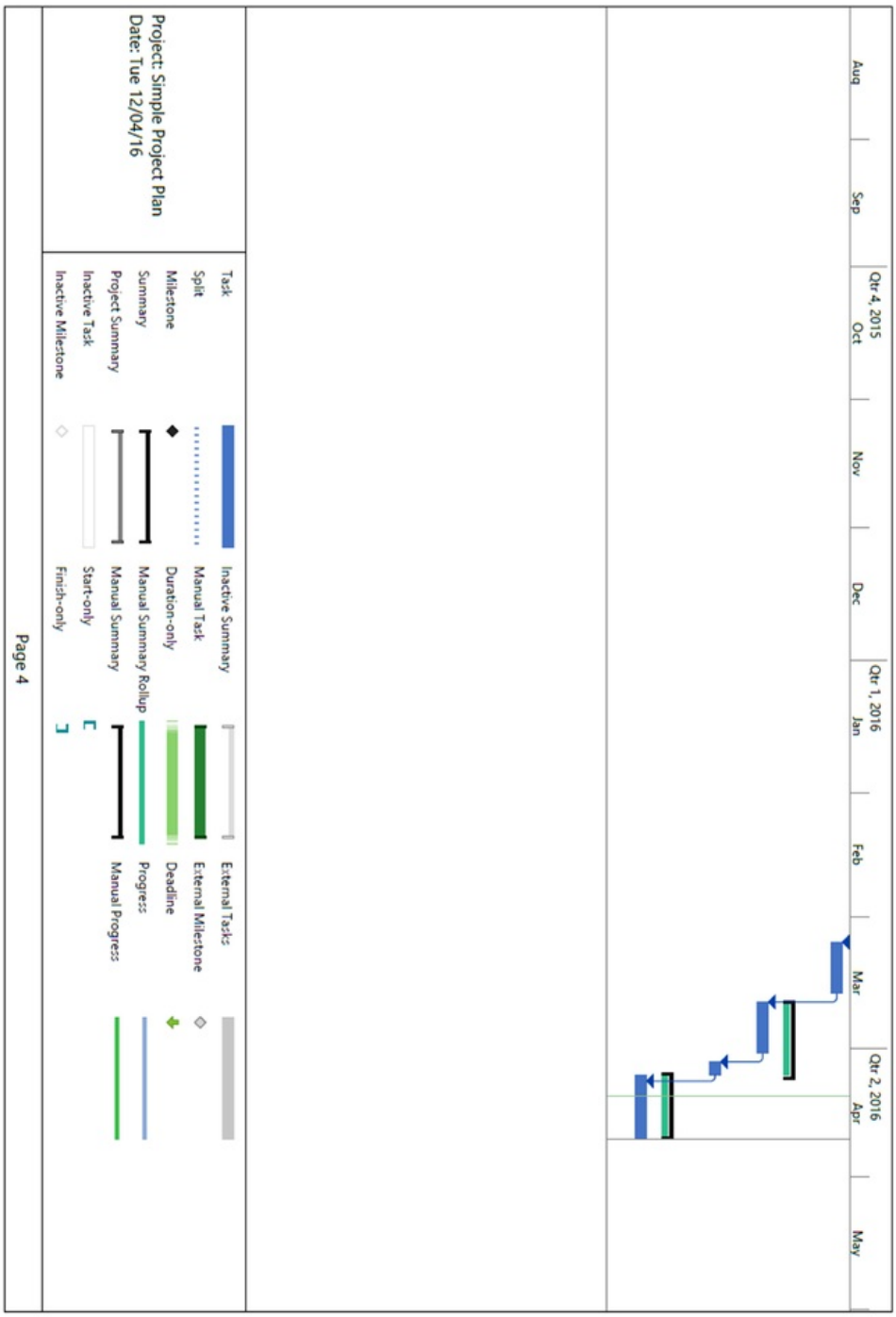
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ID	Task Mode	Task Name	Duration	Start	Finish
16		Functional Testing & tweaks	10 days	Mon 07/03/16	Fri 18/03/16
17		**Analysis**	**14 days**	**Mon 21/03/1**	**Thu 07/04/16**
18		Analysis of laser performance	10 days	Mon 21/03/16	Fri 01/04/16
19		Possible enhancements	3 days	Mon 04/04/16	Wed 06/04/16
20		**Final Report**	**11 days**	**Thu 07/04/1**	**Thu 21/04/16**
21		write final report	11 days	Thu 07/04/16	Thu 21/04/16



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Aug
Sep
Qtr 4, 2015
Oct
Nov
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Qtr 1, 2016
Jan
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Qtr 2, 2016
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May
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Appendix 6 – System Code

Appendix 7 – Parmley Grayham Quote