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Research article

Motion optimisation for improved cycle time and reduced vibration in robotic assembly of electronic components

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Abstract: Traditionally, six axis robots have not been used in electronic surface mount assembly. However, the need for more flexible production systems that can be used for low to medium production builds, means that these robots can be used due to their high degrees of flexibility. This research investigated the application of an articulated robot to assemble a multi component PCB for an electronic product. To increase the potential of using this method of automation, a genetic algorithm was used to improve cycle time and condition monitoring was performed to assess the vibrations within the robot structure, during operation. By also studying the motion types the robot movements can be optimized in order to minimize the cycle time and maximize the production throughput with reduced vibrations to improve the accuracy of the assembly process. The study utilised a robotics assembly cell and a robot programmed with different velocities. Vibrations were present throughout out the assembly cycle and by analysing when these large vibrations occur and for which types of motion, an optimal selection could be made. The point-to-point motion type running at 50% speed had a faster assembly time and significantly lower accelerations and oscillations than the other motion types. The spline-linear motion type running at around 30% speed was best for the component insertion due to its linear nature and improved repetition accuracy.

Keywords: genetic algorithm; assembly optimization; electronics assembly; KUKA robotics; condition monitoring

Abbreviations: PTP: Point to Point; SPTP: Spline Point to Point; LIN: Linear; SLIN: Spline Linear; GA: Genetic Algorithm; SCARA: Selective Compliance Assembly Robot Arm; IC: Integrated Circuit; SIL: Single In Line; PCB: Printed Circuit Board; DOF: Degree of Freedom; KRL: KUKA Robot Language; α (alpha): Degree of Rotation; *d*: Distance; *h*: Height

1. Introduction

Electronics manufacturing has evolved over the past years from a labour-intensive activity to a highly automated one. Assembly processes and are often considered to be one of the cost intensive systems in manufacturing. Furthermore, the competition faced by electronic component manufacturers results in a need for high throughput rates for which automated assembly lines are a major asset [1]. Implementation of robotics in assembly of electronics offers some distinct advantages over manual methods due to its reliability and flexibility. Assembly of electronic components is a complicated task; several technologies that utilise sophisticated machines are used in industry to perform intricate operations. Automated assembly systems usually comprise of several sub-systems, including: part feeding systems, work holding and pick and place devices. Depending on the application, various types of robots can be used for pick and place operations; e.g., gantry/Cartesian robot, cylindrical robot, spherical robot, SCARA (Selective Compliance Assembly Robot Arm), and spider robotic arms [2,3]. Despite its popularity, the articulated robot type has been widely neglected for printed circuit board (PCB) assembly due to its relatively higher equipment prices. Articulated robots have the potential to become more popular in the industry of electronics due to high degrees of flexibility, excellent repeatability and now also due to lower investment cost and competitive prices. Prior to soldering, electronic components need to be placed into position, on the PCB, and the use of automation and robotics provides accuracy, repeatability and efficiency to this process, when compared to manual assembly. One such process is the manipulation and placement of electronic components, prior to soldering, using a robotic arm in a low volume production setting. The low volume production challenge is important as new industrial strategies for high value 21st Century Products need to consider flexible manufacturing methods. In this research, the test part is a Eurorack Serge filter with variable resonance. This electrical product lends itself to mass production systems that traditionally would have used production lines with high manual costs and more recently high investment specialised automation. However, in this automation research a non-specialised system is used. In this way, the research will investigate the application of a robotic system that can be flexible in producing multiple part and build options, while meeting the precision, efficiency, reliability and repeatability of a dedicated automation system.

The main contribution of this paper is the use of a genetic algorithm in the optimisation of path motion and vibration reduction, for an articulated KUKA robot with six degrees of freedom in a pick-and-place operation. The investigation into the optimisation process of robotic assembly for specific electronic components was conducted. The example device includes a front panel and - two component printed circuit boards connected through single in line (SIL) headers. Each of the PCBs consists of numerous parts, such as, switches, jack ports, potentiometers and electronic components; resistors, capacitors, transistors and fuses.

In a previous study, the optimal path and feeder allocation was found using a heuristic genetic algorithm approach. The build routes were programmed into the KUKA robot and timed to verify the use of the algorithm. The algorithm was successful in optimising both the feeder allocation and build route to reduce overall projected distance and cycle time. To further optimise the assembly process, this paper contributes a study into the motion types available for use in the KUKA robotics system with the aim of addressing the following:

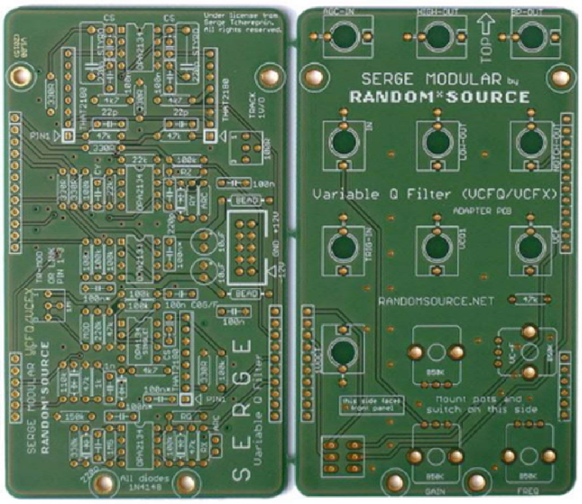
- Correct motion type selection for fastest cycle time, assuming the build route and work space orientation have already been optimised.

- A study into the vibrations caused by each motion type in order to determine ideal speeds, reduce wear and improve accuracy. This is performed using a developed condition monitoring system throughout the entire assembly cycle time.
- An investigation into how the robot behaves when performing single step assembly motions and the accelerations and oscillations occurring during movement in a small time frame.

2. Eurorack Serge filter

2.1. Example device details

The Eurorack Serge filter was chosen as the focus of the study due to its suitable complexity and variety of components. The assembly operation of the printed circuit board can be achieved using a variety of placement technologies; however the main focus of this paper is to present the procedure of finding the best solution for articulated type robots with six rotary joints. With >60 resistors diodes and capacitors, 14 potentiometers, 8 ICs and 4 power components the filter provides a good representation of the PCBs that would be prototyped or produced in small batches using a six axis robot as opposed to more permanent pick and place operations for many thousands of cycles. Assembly systems typically have the facility for holding the circuit board in place and a magazine equipped with feeder racks for component supply by various end effectors. The assembly operation starts with placing and fixing the circuit boards in the holding jig, which is usually designed according to a poke-yoke principle. Then using the articulated robotic arm the components are sequentially collected from stationary feeders located along the side of the holding jig and transferred onto their designated place on one of the two circuit boards (Figure 1).



(a) (b)

Figure 1. Eurorack Serge filter PCB 1(a) and PCB 2(b).

The Eurorack Serge filter consists of two PCBs with 100 components between them that have to be placed and soldered. The first PCB consists mostly of resistors, capacitors and diodes, while the second has larger components such as jack ports and potentiometers. Using the genetic algorithm, the build sequence and feeder assignment problem have already been optimised along with workspace arrangement. The genetic algorithm was proven to be reliable in finding good quality solutions to both of the combinatorial problems. The feeder slot assignment problem was solved to find the best allocation of the various component types based on their position on the circuit board. The order of component placement has also been optimised to reduce the total distance travelled by the KUKA robot end effector in a single assembly cycle.

Due to the delicate nature of the components and the small location holes, accuracy and repetition capabilities are major factors in the success of the articulated robot assembly method. Therefore by conducting a study into the optimisation of robotic motion and vibration reduction, the accuracy and viability of the assembly technique can be validated.

3. The genetic algorithm adopted

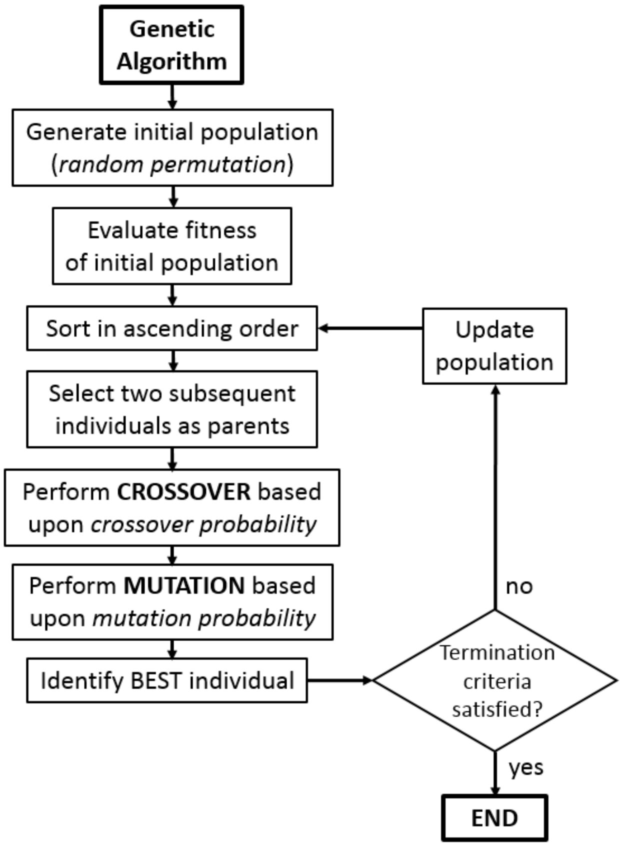


Figure 2. Genetic algorithm flowchart.

The genetic algorithm technique was first introduced by Holland (1975) [4]. It is one of the heuristic methods inspired by the well-known biological processes of genetics and evolution to find a near-optimal solution to an optimisation problem. In this method, a candidate solution is represented as an individual with a set of properties called chromosomes and the group of individuals is called a population (Figure 2). At the beginning of the algorithm, an initial population of chromosomes is generated through random permutation. In the following phase, the population evolves to the next generation through crossover and mutation. Pairs of chromosomes are selected and the crossover operator is applied to produce offspring. The offspring can then mutate according to set mutation probabilities [5]. After the reproductive operations, the fitness of the offspring is assessed and compared against the parents. Based upon survival of the fittest rule, the best individuals of the offspring are selected for the next generation. The genetic algorithm runs until termination criteria are satisfied or no improvement is observed during a number of generations. As a result, the best candidate solution represented as the fittest individual is found. This technique was used to determine the best solution for both the feeder allocation and assembly sequencing problems prior to this investigation [6].

4. Motion types

The KUKA robot offers six different types of path motion. Two of these will be disregarded as they are circular motions, which are not relevant to the proposed problem. The motion types available for the electronics assembly are as follows:

- Point to Point (PTP) – This motion type involves following the quickest path between two points. So in this case, as the end effector follows a path between a feeder and component position it will calculate the quickest path between the two points. Because the robot axes are revolute this may not be a straight path. It is quicker for the robot to rotate using fewer joints than constantly move all required joints for a straight path.
- Linear (LIN) – The linear motion type follows a straight path and uses more joints in constant motion to trace the straight path. This is used when a straight line is necessary or if straying from the path would cause a collision to the work surface.
- Spline Point to Point (SPTP) – This is similar to the PTP motion, however it allows for continuous spline motions where points are estimated and a smoother motion is available.
- Spline Linear (SLIN) – As with the SPTP this motion type uses splines between linear motions.

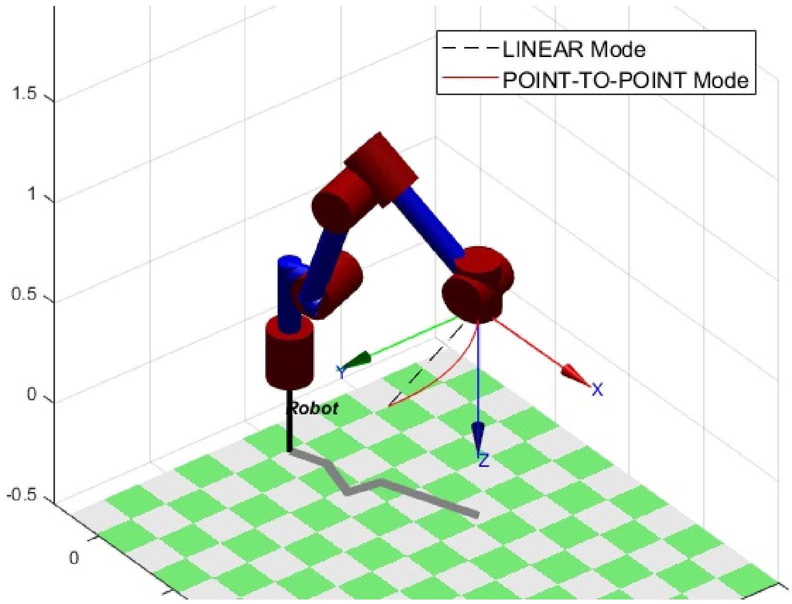


Figure 3. KUKA robot model plotted using Robotics Toolbox for MATLAB.

The difference between the PTP and LIN motion types can be seen in Figure 3. The effects on the cycle time for each motion type were tested using the same sequence and feeder arrangement. By making this comparison a solution can be obtained that not only reduces the cycle time through good placement sequencing, but also through direct optimisation of movement using the best motion type. Figure 3 presents the KUKA KR16 model created in the Robotics Toolbox for MATLAB according to the robot specification. Thick cylinders correspond to the robot's six revolute joints and thin cylinders symbolise robot arms. In addition, the XYZ axis presented on the plot is the origin point corresponding to end effector position. Two different paths were plotted along the y axis at the approximate height of the end effector: straight line (black, dashed) indicating shortest route between two points (LIN) and curved path (red), symbolizing the fastest route.

4.1. KUKA details and KRL methods

In conjunction with the SERGE filter test part, the study was conducted using a KUKA KR16 six axis industrial robot (Figure 4). The KUKA industrial robots are highly accurate with a position repeatability of +/- 0.05 mm [7]. This is a precision suitable for the test part assembly.

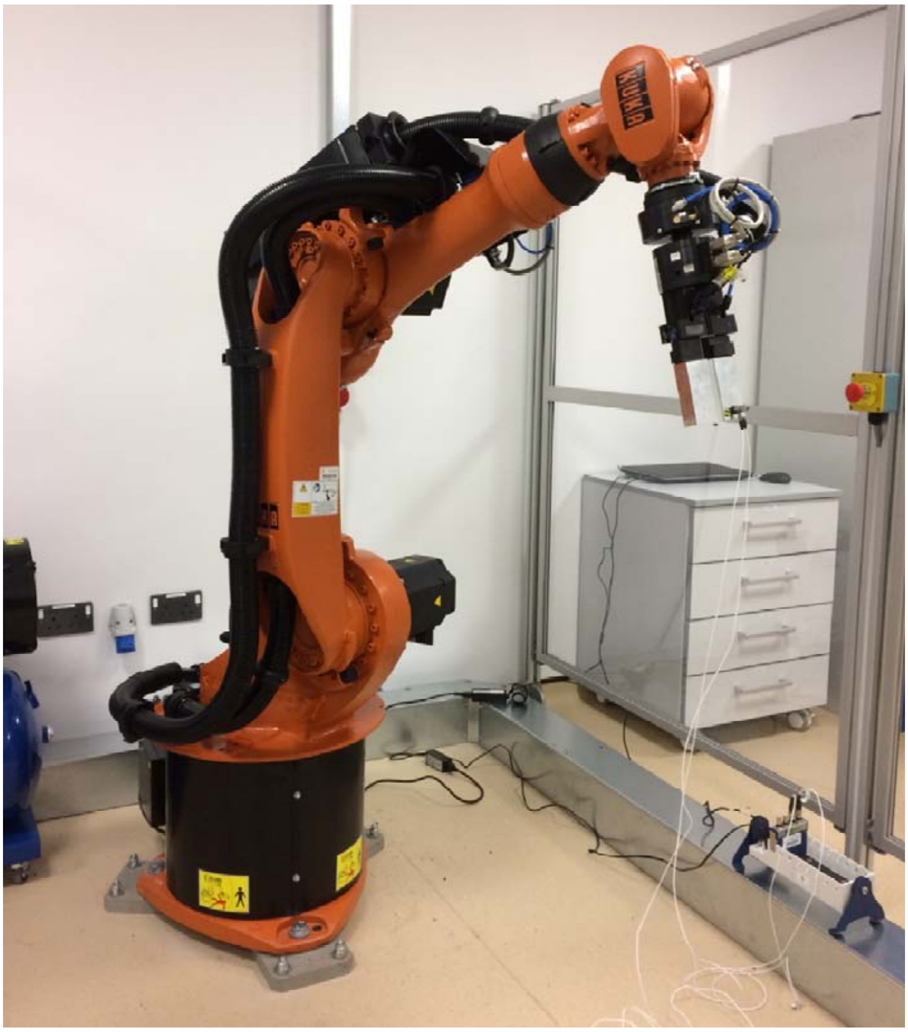


Figure 4. KUKA KR16 model industrial robot.

Once the sequence and feeder slot designation had been produced from the genetic algorithm, the path had to be programmed into the KUKA robot. The KRL can be used to program the robot online or offline. The quickest online method was performed using the KUKA Smart Pad. A jig was set up on the assembly worktable with the PCBs held securely and the end effector could be positioned anywhere over the surface. The locations of all the feeders and component positions were saved as way points using the teach method by moving the end effector to the relevant location and recording a named point. The sequence could then be programmed by simply using a motion command and renaming it to the desired point. This allowed for the quick programming of several sequences and with various motion types. Within the sequence, timer commands were added to start recording at the first point and stop recording at the end. In order to assure accuracy, a zero second wait function was placed before each timer function to ensure that in real time, the end effector reaches the desired place before the timer initiates. This was necessary because the KRL reads ahead in the code and so it was found to be implementing the timers prematurely. Only the transverse motions of the end effector moving the components to the feeders was programmed because regardless of sequence order the global Z motion and gripper actuation takes the same time. Thus it was not necessary for a comparison to be made between sequences. Once the build sequence was programmed on the KUKA the programme is run and check for accuracy in terms of position and the capability of loading the components to the PCB. Only after optimisation of the part trajectories and the identification of the correct speeds is the program considered for vibration assessment.

4.2. Vibration study experimental setup

In this study, vibrations within the KUKA robot, during operation in various motion modes, were assessed. The total cycle assembly cycle was performed for the four motion types; SLIN, LIN, SPTP and PTP. Vibration data was recorded throughout the cycle in order to give full details of the maximum accelerations occurring within the robot structure. Vibration reduction allows for an improvement in error margins for many industrial robotic processes [8]. Within the robotic manufacturing and assembly industry, vibrations can reduce the overall quality and efficiency of a process [9,10]. The vibrations were measured using ICP 352C03 Piezo accelerometers (Table 1). Two were positioned on the robot end effector as this is the point of the robot that is under constant motion and requires the positional accuracy to place the electronic components into the PCB (Figure 4). The accelerometers are directional and so Accelerometer #0 was aligned to the global Y axis and Accelerometer #1 was aligned to the global X axis. When the robot arm is under motion the accelerometers measure vibrations within the structure using a varying piezoelectric charge. The piezoelectric charge signal from the sensors is converted into an output voltage proportional to the acceleration. The sensor output signals are then downloaded onto a computer using a National Instruments cDAQ-9172 USB data acquisition unit and the measured values were accessed through the National Instruments Labview 8 software. The national instruments modular DAQ was connected to the computer and the accelerometers were connected to the DAQ. Accelerometer 0 was plugged into channel 0 on the DAQ and Accelerometer 1 was plugged into channel 1. The Labview software was designed such that the signals from the DAQ are split and the voltages converted to accelerations. This was achieved by dividing the voltage signal by the unique sensitivity (in mV/ms^{-2}) of each accelerometer. The acceleration data is then represented graphically and automatically saved to an LVM file.

Alongside the study of the entire cycle time, analysis was performed to investigate the behaviour of the robot during a single motion. The Labview program was altered to capture acceleration data over a much shorter period of time. The capture rate was increased and the number of samples was decreased to produce 3 seconds of vibration data. This made it possible to perform close up analysis of a single transverse motion and the display of the decaying oscillatory vibrations occurring within the robot structure itself.

One of the most important motions performed in the assembly cycle is the insertion of the components, the accuracy is paramount in this movement due to the small location holes and delicate components. This motion was performed and the vibrations measured similar to the transverse motion but in the global Z axis direction.

Table 1. ICP 352C03 Piezo accelerometers specifications.

Sensitivity	1.03 mV/(m.s^2)
Measurement range	+/- 4900 M/s^2 pk
Resonant frequency	>50 KHz
Non Linearity	< 1%
Traverse Sensitivity	< 5%
Excitation voltage	18 to 30 VDC

5. Results

5.1. Optimal motion type

The genetic algorithm was used to find the shortest and conversely longest paths. These represent the “best” and “worst” solutions. Between these solutions there is over a 2 second improvement per cycle for the SLIN motion type, which is commonly used in this sort of operation (Table 2).

Table 2. Comparison of recorded best and worst solution times for all motion types.

Time results based on	Robot motion type			
genetic algorithm solutions	LIN	SPTP	SLIN	PTP
Best Time [ms]	107,796	94,284	93,264	56,340
Worst Time [ms]	119,604	96,936	95,460	60,108
Difference [ms]	1,1808	2652	2196	3768
Percentage Difference	10.95%	2.81%	2.35%	6.69%

Using the solutions created with the genetic algorithm, a time difference between the best and worst has been found. Depending on the motion type (LIN, PTP, SLIN, SPTP) the improvement was found to be between 2 and 11 seconds (Table 2). The motion type has a large effect on the speed of the path followed. As can be seen from the results the PTP motion type is far quicker than the others however, while slowest, the LIN motion type offers the greatest improvement between the best and worst. This is however negated by the quicker motion types. There are drawbacks to the faster motion types; at faster speeds (particularly PTP motion) increased vibrations are observed in the robot structure during operation. This could cause increased wear in the robot and reduce repetition accuracy within the process. The nature of the assembly process requires high levels of control and accuracy and it would be potentially damaging to the robot to run at full speed with PTP motion. Because of this, the PTP motion type was retested at lower speeds to reduce the vibration within the robot and, at 50% velocity with an allowable maximum of 1 ms^{-1}, the time was 79956 ms, which is still quicker than the next best motion type (SLIN). The SPTP motion type performed worse than expected and it is theorized that this is due to the increasingly complex calculations performed by the robot and a notable "thinking" time was observed between movements.

5.2. Assembly cycle vibration analysis

After performing the cycle time analysis the unwanted vibrations occurring were investigated. The robot structural vibration experiments were performed for each motion type based on the genetic algorithm best solution results. The whole assembly cycle was recorded and the data exported. The following graphs were created to show the distribution of maximum vibrations for each motion type with two accelerometers. The histograms show how frequently each level of vibration occurs across the entire assembly process (Figures 5–8).

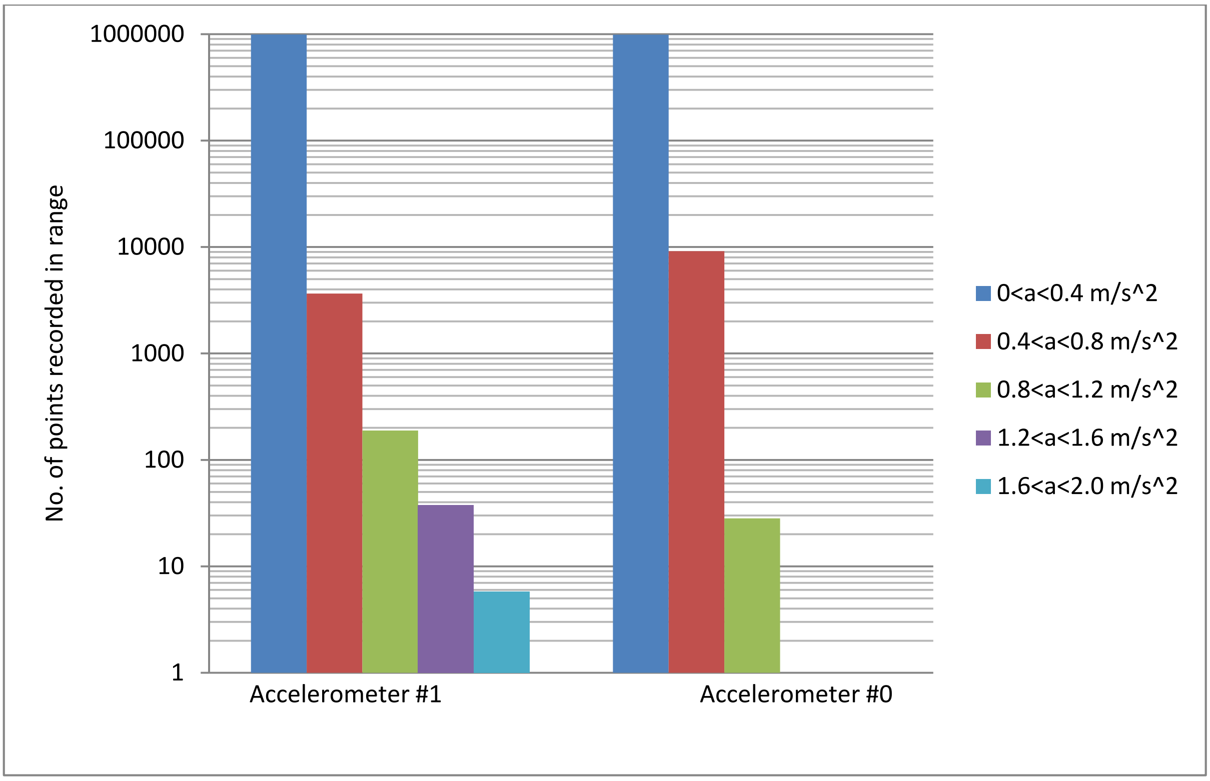


Figure 5. Histogram of the PTP vibration ranges.

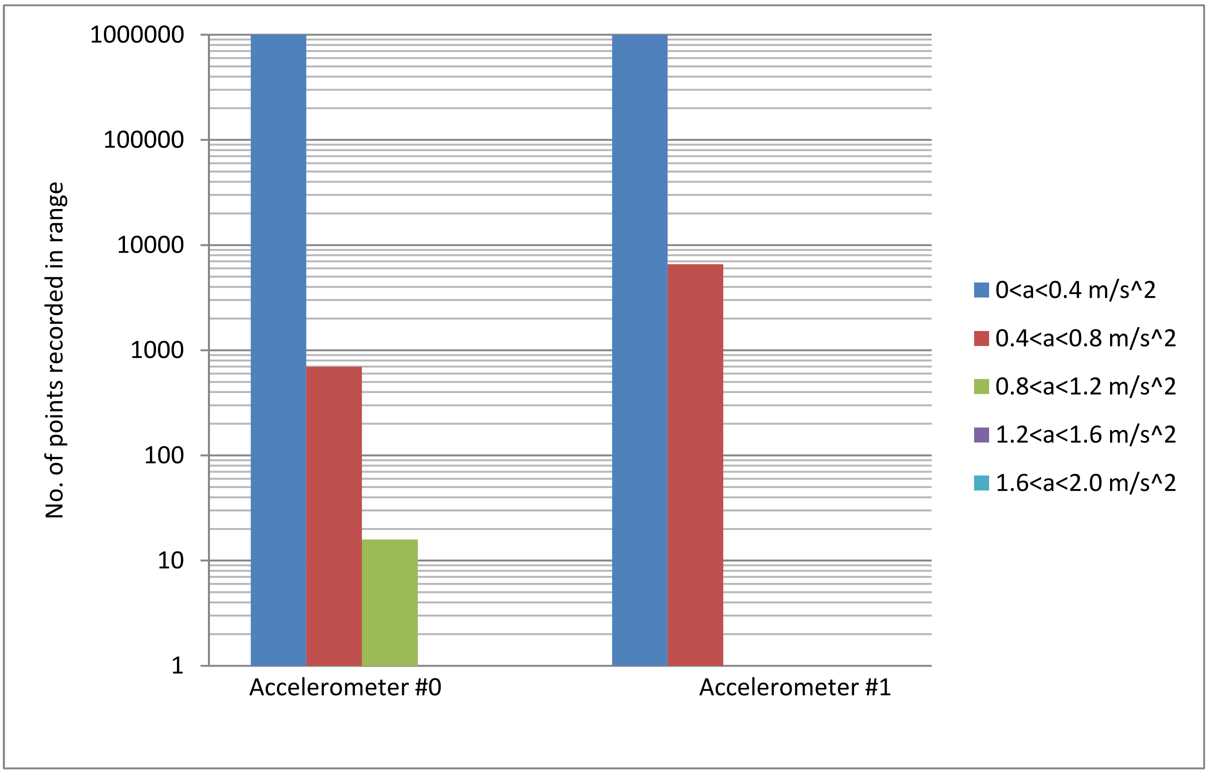


Figure 6. Histogram of the LIN vibration ranges.

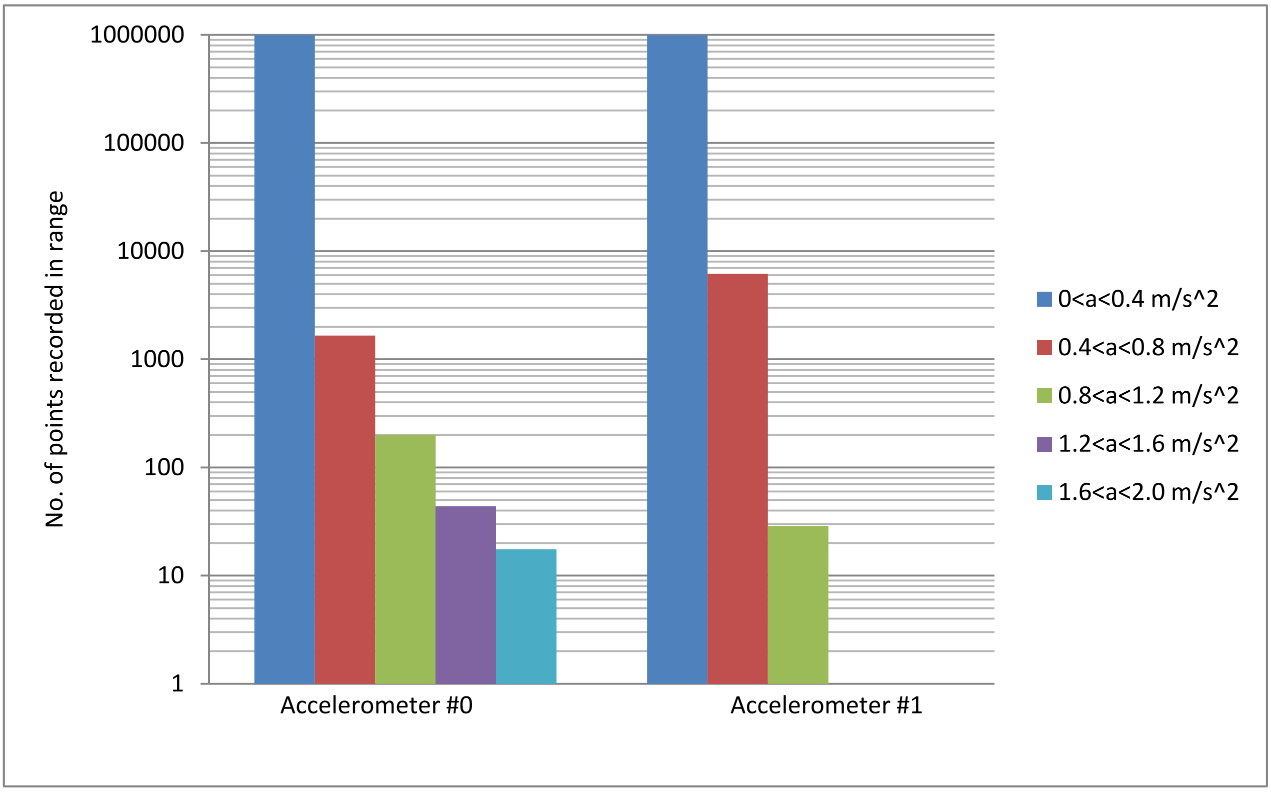


Figure 7. Histogram of the SPTP vibration ranges.

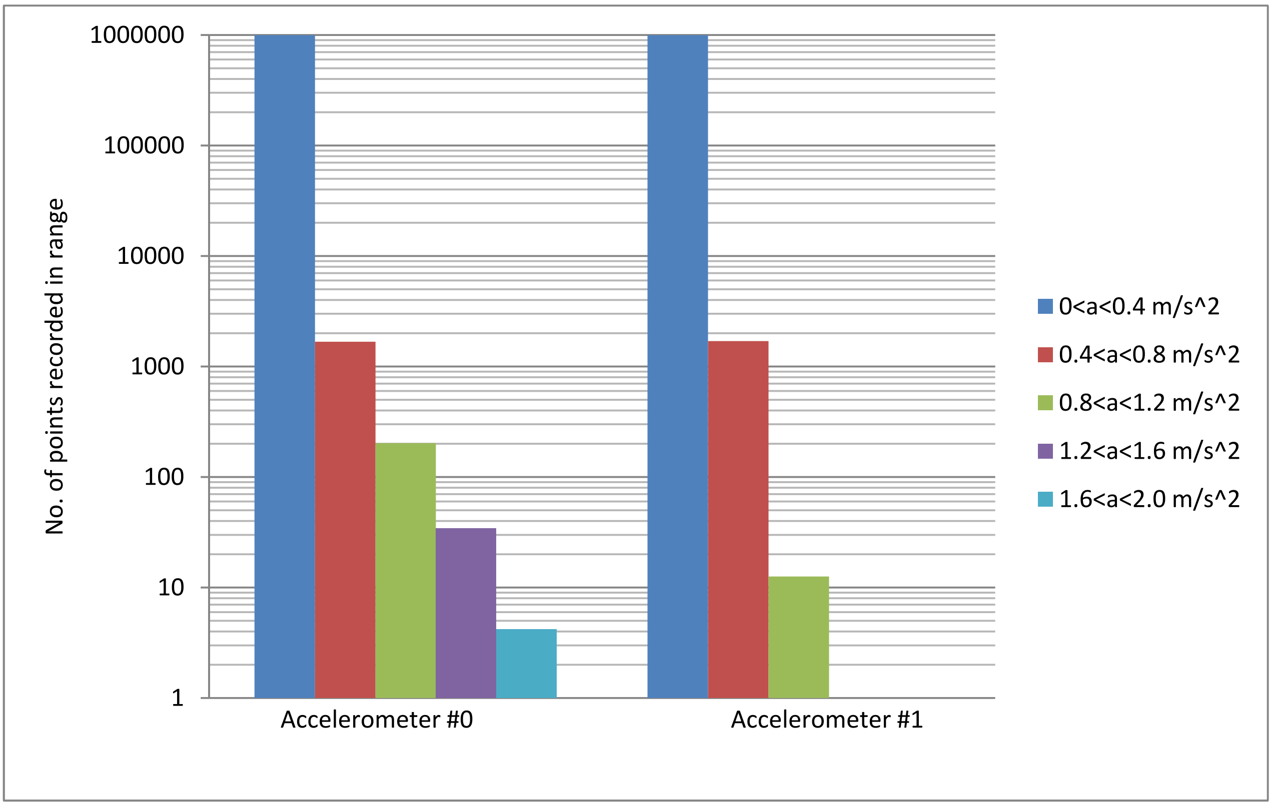


Figure 8. Histogram of the SLIN vibration ranges.

Most of the accelerations fall in the range of 0 ms^{-2} to 0.4 ms^{-2} with Accelerometer #0 at its peak between 1.6 ms^{-2} and 2.0 ms^{-2} for each motion type apart from LIN which peaks two groups lower at 0.8 ms^{-2} to 1.2 ms^{-2} (Figure 6). This shows that the maximum accelerations occur in the global X axis direction of the robot. This is visible during the assembly operation when the robot moves forward from a feeder to a component entry position. This motion has higher acceleration than the Y axis motions in the assembly operation. The lower accelerations exhibited by the LIN motion type are reflected in its much higher assembly cycle time. This is not the best option in terms of optimisation for fast production output due to the long cycle time. The choice of motion type is a compromise between fasts assembly time and low vibration levels. The SLIN motion type offers the best speed after PTP and shows fewer high acceleration levels when compared to SPTP and PTP. Therefore SPTP is ruled out as the optimal motion type due to its comparably higher cycle time and higher vibrations than the SLIN motion type.

As was found in the cycle time study, when reducing the speed at which the PTP operation is performed, the cycle time is still shorter than the next best motion type. In order to assess the improvements this has in terms of vibrations within the robot, a further cycle time vibration test was performed. As can be seen in Figure 9 the peak vibration occurring at half speed for PTP motion is reduced to the range of 0.8 ms^{-2} to 1.2 ms^{-2}. This is also an improvement on the next best motion type of SLIN. Therefore by halving the speed of operation, the vibrations have been greatly reduced while still having a cycle time faster than all other motion types. This is a step toward a fully optimised process. Depending on the allowable vibration levels the speed can be reduced appropriately while still shortening cycle times for assembly operations.

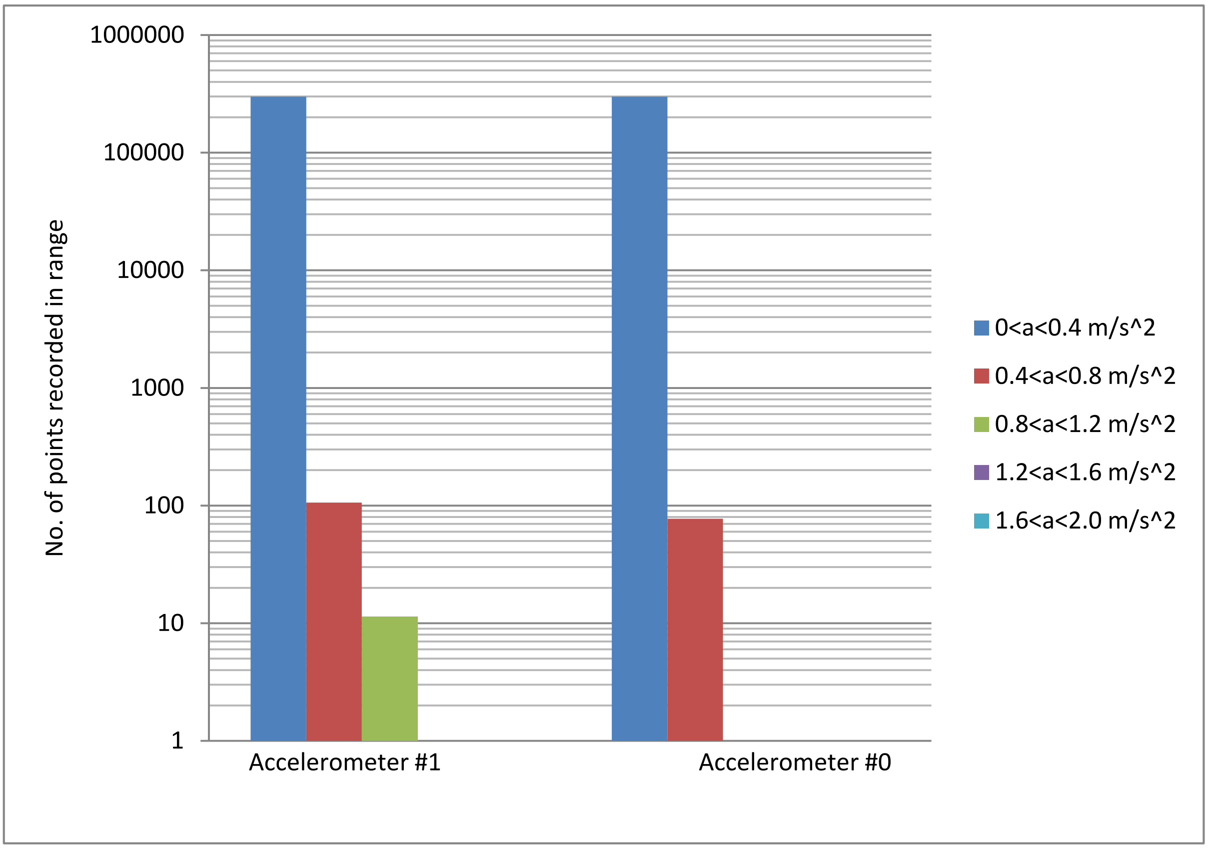


Figure 9. Histogram of the half speed PTP vibration ranges.

5.3. Single motion oscillation study

The single motion study was performed by shortening the number of data points and increasing the rate at which the DAQ captured the data. This created a 3 second recording window. The motion was a movement of approximately 200 mm in the global X axis direction. Figure 10 shows the oscillations present in this PTP motion in the form of acceleration data varying with time.

The solid blue line represents Accelerometer #1 which was orientated to the global X direction. The dashed red line shows Accelerometer #0 which was orientated to the global Y direction. As expected, the blue line peaks much higher than the red line due to the motion being performed in this direction. Higher levels of acceleration occur in this direction as the robot accelerates and decelerates. Interestingly, there is notable oscillation present in both lines. This suggests a vibratory acceleration is occurring in both directions and this is merely amplified in the global X direction due to the movement. So in fact, what is being seen is a spike in vibration surrounded by oscillatory decay and some background noise. Despite the background noise that can be seen in the first portion of Figure 10, a clear decaying pattern is visible after the initial spike. There is some noise overlaying the decaying oscillations which would be difficult to filter out in the working environment or post processing without causing drift in the data. However Figure 10 concludes that the vibrations suspected to occur, as the robot reaches the end point of the PTP arc, are present. The test was performed multiple times for the same motion and the results were consistent repeatable. Figure 10 was chosen because it exhibited the increased vibration phenomena most clearly and no alterations were made to the raw data exhibited in the graph.

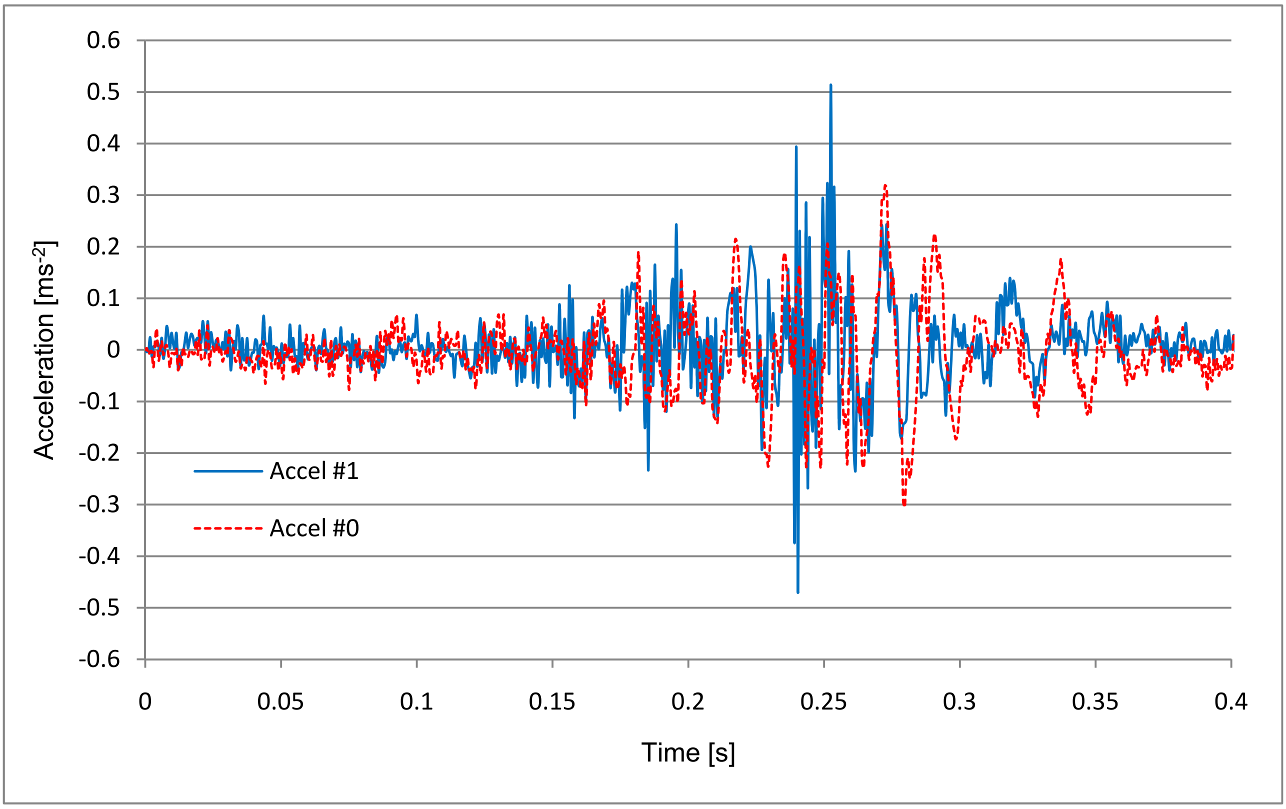


Figure 10. Single motion oscillation graph.

5.4. Component placement vibration study

Similarly to the single motion study, the robot was programmed to perform one motion in the global Z direction. This represents the placement of the electronic component. As this process requires great accuracy and precision vibrations would be unwanted and could cause placement issues. At lower speeds of 30% to 40%, the component placement is performed seamlessly with no issues, however, as the speed of movement is increased toward the full 100% depicted in Figure 11, vibrations start increase. This is also noticeable during the actual component placement operation. As the robot inserts the component into the PCB there is an audible click that identifies interference due to the pins being misaligned to the mating holes on the approach to the board.

The amplitude of vibration does not peak much higher than the background noise for Accelerometer #0. Accelerometer #1 peaks 0.1 ms^{-2} higher than the background noise. This is not a large acceleration change and so is not detrimental to the operation of the robot, however, it does present some issues for the placement accuracy. Even the smallest straying from the prescribed path at 100% velocity can cause inconsistency in component placement. The vibrations observed in Figure 11 can be considered as a potential assembly failure cause. The suggested solution is to reduce the speed by at least 70%. When performed, this reduction showed greater consistency and smoother component placement. The placement motion should also be of the linear form to avoid an arc path being followed that interferes with other components on the board.

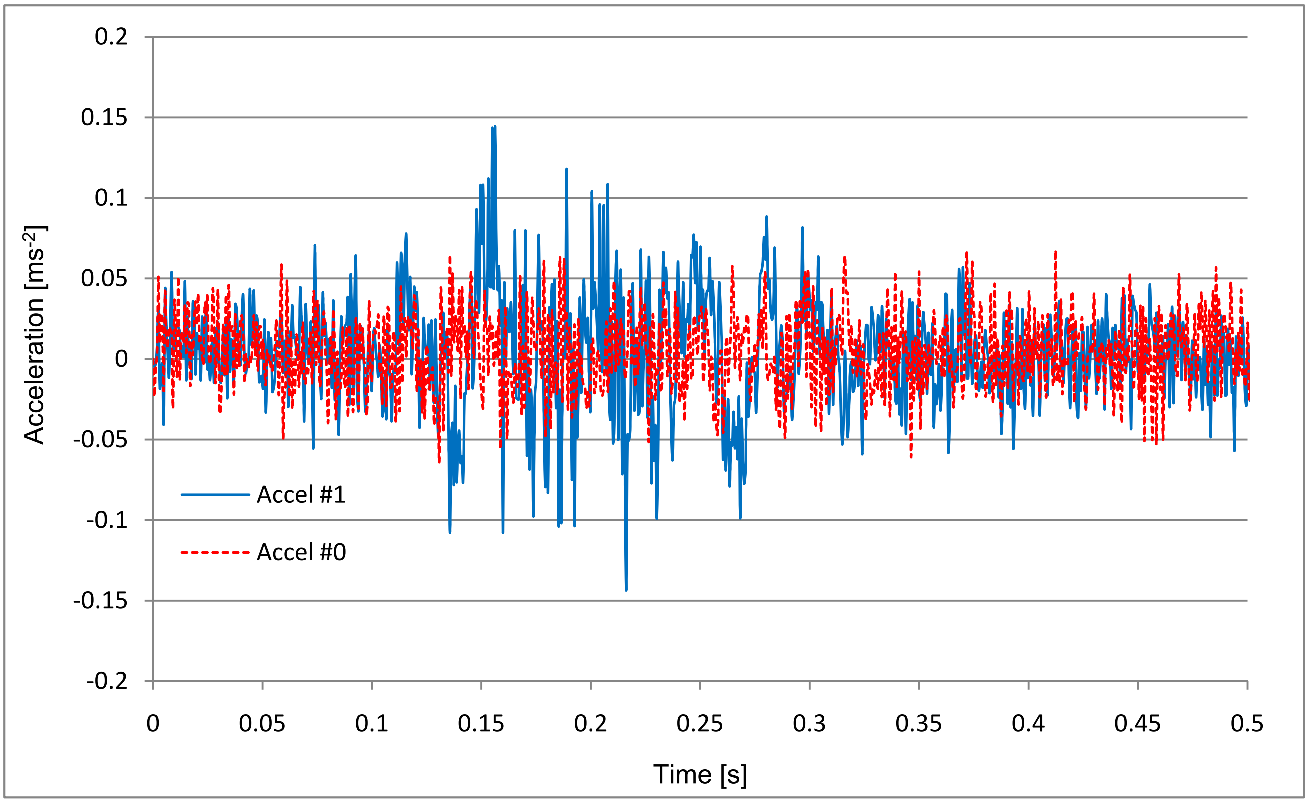


Figure 11. Placement motion oscillation graph.

6. Conclusions

In this paper, a compact antenna array was proposed for UWB MIMO communications. The dimensions of the two-element antenna array are 44 mm × 27 mm × 0.8 mm which are small enough for the antenna to be considered for portable wireless devices. The antenna is fed via CPW feedlines. This facilitates the connection of the antennas with active and passive elements (for matching and gain improvement) and integration with MMIC circuitry. The antenna has been fabricated on FR4 substrate and the experimental results confirm the UWB coverage for the proposed structure. The radiation pattern of the antenna elements is quasi omni-directional in particular at lower frequency range. To reduce coupling, a T-shaped slot was introduced as a decoupling structure between the two radiation elements. Besides, the computed ECC values for the antenna are extremely small over UWB frequency range confirming the excellent performance of the antenna in the UWB MIMO applications.

This research investigated the application of a manipulator robot to assemble a multi component PCB for an electronic product. The approach considers the need for a highly flexible automation system for medium and low volume manufacture. This non-traditional assembly method bridges the gap between time consuming and costly manual builds and the high-volume production lines using dedicated high investment automation equipment. To increase the potential of using a highly flexible robot with six degrees of freedom, a study into the optimisation of robotic motion and vibration reduction was performed. The assembly process was previously optimised using a genetic algorithm to determine the best feeder allocation and component placement sequence. The vibration reduction investigation utilised a KUKA KR16 robot within a robotics assembly cell, and accelerometers linked to a modular DAQ and Labview program. The method was successfully implemented for determining the vibration patterns occurring over the complete cycle time and for single motions. The best robotic motion type was determined and validated using a number of experimental techniques. The main findings are as follows:

- From the cycle time analysis performed on the best assembly solution, it can be concluded that the PTP motion type is faster than the other motion types by at least 40 seconds. Over a large number of cycles this saving will add up to a vast improvement in efficiency and throughput.
- While the PTP motion is the fastest, it also caused the most high frequency oscillations within the robot. This increased vibration could reduce the accuracy, and constant vibrations can cause wear over a large number of cycles. When compared to the other motion types the PTP had the highest peak amplitude, and large acceleration levels were more common.
- It was found that by running the PTP path solution at half speed it was still faster than SLIN, the next best motion type. By performing a vibration study at half speed it was found that on average the PTP assembly path had reduced vibration and acceleration amplitudes when compared to the other motion types.
- For a single transverse motion in the global X direction Accelerometer #1 had the higher amplitude spikes in oscillation compared to the other accelerometer. A clear decaying oscillation pattern was visible for the single PTP motion at 100% velocity. This confirms that the inaccuracy and shaking effect previously observed is due to oscillations within the end effector. By reducing the speed these vibrations can be reduced, which is necessary for accurate movement above the PCB
- As the robot moves to place the component in the global Z direction, vibrations were occurring in a similar pattern to the transverse motion, but to a lesser extent. This is likely the cause for the misalignment and audible noises due to interference of the assembly step as the robot places the components at 100% velocity. The repetition accuracy increased greatly just by reducing the speed of insertion and using a linear motion type.
- During the vibration tests some background noise was always present. This is likely due to the environment and running of multiple robot axis. For the majority of the assembly cycle the vibrations did not exceed this background noise level however in longer movements some overlay of noise was visible in the acceleration graphs. Multiple tests were performed for each experiment and the averages taken to reduce the likelihood of background noise anomalies affecting the data. The noise would be hard to filter out during the experiments and any post processing could cause drift in the data. Therefore there will always be a small amount of background noise present during the running of the robotic assembly cycle, but not to an extent that causes inaccuracy in the process.

By reducing the speed and selecting appropriate motion types for different actions in the assembly cycle the robot can perform the optimised assembly process with accuracy and repeatability. The application of a genetic algorithm to reduce cycle time, together with condition monitoring to reduce vibrations allow for a very flexible and efficient solution for assembling electronics.

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Conflict of interest

The authors declare that there is no conflict of interest.

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