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Statistical analysis of automation actuator response times

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Abstract

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Abstract

The aim of the study was to find the statistical significance of physical effects on automation actuator response times. A simple cyclic program was created using TIA Portal and uploaded to a PLC. Different pistons and valves were then tested and recorded using the TIA Portal trace measurement system. The results were then exported and analysed using IBM SPSS. The major predictor was found to be the direction of the actuation, which was affected by both the type of valve and piston used. Contrasting the findings to the digital effect on response times as provided by Siemens S7-1500 cycle and response time manual, it was concluded that the physical effects on response times were smaller in magnitude, but more persistent.

Keywords

automation, response times, statistical analysis

Contents

1 Introduction

As automation becomes more prevalent worldwide, the reliability of automated systems becomes a more pertinent concern in automation. Considering the increasing mass of automated solution implementations, the mass of inconsistencies in performance becomes larger in tandem. Provided by the manufacturers of automation solutions, the effects of CPU - and digital communication load are quite well documented. However, as digital technology progresses, it was hypothesized that due to the growing performance of digital systems, the actuation time would become less bottlenecked by digital processes. This would in turn make the physical properties of the automation devices grow in significance in comparison to the digital. The following research was made with the intention of providing a simple and clear-cut way of analysing and finding physical and mechanical contributors to actuation time variability and their relative significance.

Using a simple setup of mechanical and digital actuators and two different pistons, the digital communication aspect was eliminated for the sake of discerning the purely mechanical aspects of actuation variability. However, a short foray into the nature of the communication was also made.

The main method used in the study was to group the data recorded from the experiments according to different variables, and to look for maximum and minimum actuation times in the data. The goal was then to associate them with findings made regarding the physical properties of the actuators and pistons used. The results would then be compared to extensions to the digital actuation times, as described by the manufacturers, to determine the significance of the physical effects on response time.

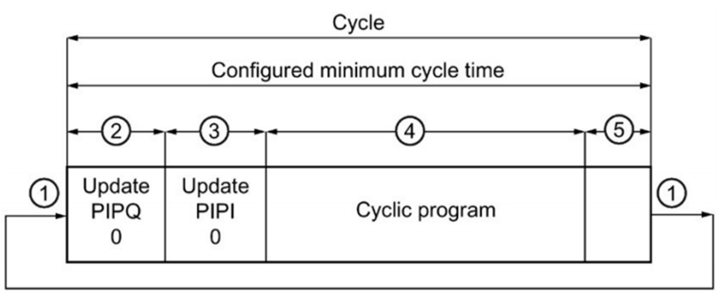
2 Preliminary information

The source for manufacturer data used in the study was the “Siemens S7-1500 Cycle and Response Times” manual. Contained in the manual were information regarding the structure of cyclic program execution within the CPU, a set of standard response times, and formulas for determining response times under different communication loads.

Measurements were made using the TIA Portal Trace measurement functionality. The gathered results were then exported as comma separated value files and processed in Microsoft Excel. The processed results were then exported to IBM SPSS statistical analysis software, where the graphs presented further on in the research were made.

Additionally, the actuators and pistons were examined to determine the physical properties which hypothetically would play a role in response time variability.

2.1 Cycle process structure



① Cycle control point at which the operating system starts measurement of the cycle time.
② The CPU writes the states from the process image output to the output modules.
③ The CPU reads the status of the inputs at the input modules and writes the input data to the process image input.
④ The CPU processes the user program and executes the instructions specified in the program.
⑤ Wait phase until end of configured minimum cycle time

Figure 1. Process cycle diagram

Presented in Figure 1 is the basic overview of the cycle program block within the CPU. Marked as 1 at either end of the cycle are the cycle control points, which mark the beginning and the end points of the program cycle. The same control points mark the cycle time statistics in the measurements made using the TIA portal trace measurement system. Starting from a cycle control point (labelled 1), the CPU then proceeds to update the Process Image Partitions (PIPQ and PIPI), and then moves into the cyclic program itself. As defined in the manual, “the cycle time is the time the CPU needs for: updating the process image inputs/outputs (PIPI/PIPQ), executing the cyclic program, all program parts and system activities interrupting this cycle, and waiting for the minimum cycle time”. As the minimum cycle time was left unparameterized and no interrupting cycles were introduced, the only digital effects that remain are the process image updates, and the execution of the cycle itself. As the physical phenomena are contained in the execution of the cycle, the only purely digital effects on response times were therefore considered to be the partition image updates.

The Siemens manual contains an equation and a table for estimating the update time of the process image update. Combined with the data in the used object block, the update time was estimated to be of negligible significance, as the later measured differences in actuation time were in the range of tens of milliseconds, whereas the update times were counted in terms of micro - and nano seconds.

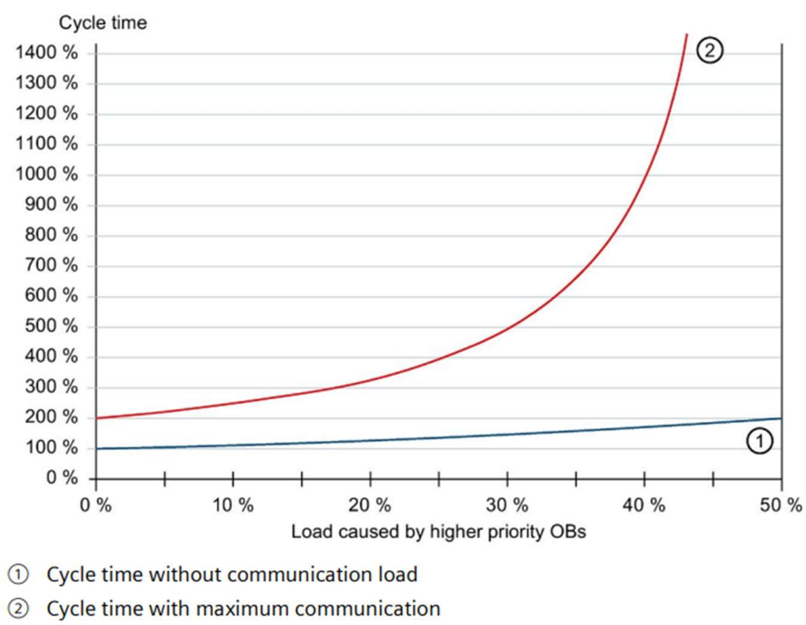


Figure 2. Maximum cycle time extension by communication load

Additional data regarding the maximum response time proved to be more difficult to account for, as can be seen in Figure 2, the response times have a nonlinear relationship to the amount of communication experienced by the CPU. The Figures show the course of cycle run time with and without communication caused by interrupting OBs. Marked as 2, cycle time with maximum communication approaches infinity when nearing the 50%. This is due to the base load of the program being 50%, so as the communication load approaches 50%, no computing capacity is left for the cyclic program. The line marked as 1 was therefore selected as one representative of maximum response time variability due to digital communication.

2.2 Data gathering and processing

Data used in the research was gathered via TIA Portal trace measurement system by downloading a signal trace configuration onto the PLC. The traced signal is picked up from the TIA portal tag table, and as such can be any input or output. The output signals were chosen for the study, as the program was created to set both extension and retraction states simultaneously. Additionally, the trace was conFigured to start on the first extended state signal so that maximum resolution could be extracted. The trace measurement has an inherent inaccuracy, as the data is segmented without relation to the state changes in the actuators. The segmentation, however, is very fine grain, as the maximum number of samples allowed by the trace measurement system exceeds 52 000 samples. With the average total runtime being approximately 2 minutes, the number of samples per second comes to around 430. To verify the results, two measurements were made, with one using a measurement being made every other cycle of the program, coined as 2-cycle, and one being made every cycle, coined as 1-cycle. Each test configuration was run for a 100 extension motions.

F2 =IF(C2=C3;0;1)

	A	B	C	D	E	F	G	H	I	J	K
1	Sample	X(ms) [18.11.2021 11:27:06	state_ext[	state_ret[%Q0.0]				state ext	state ret	t	delta t
2	75	1,63725E+12	0	1	0	0				8096,	
3	76	1,63725E+12	0	1	1,040039	0		1	0	18970,37	10873,68
4	77	1,63725E+12	0	1	2,090088	0		0	1	19123,02	152,6499
5	78	1,63725E+12	0	1	3,170166	0		1	0	19321,45	198,4299
6	79	1,63725E+12	0	1	4,22998	0		0	1	19494,23	172,78
7	80	1,63725E+12	0	1	5,280029	0		1	0	19696,32	202,0901

Figure 3. A-D raw data, E zero-time, F If statement, H-K extracted states, times and delta

The collected data was then exported as a .csv file to be opened in Microsoft Excel. Using Excel, the data was trimmed to remove beginning and end records together with any obviously fallacious measurements. A relative zero-time was then created using the formula in Figure 1. Using the actuator state tags from the measurements, an IF statement formula was implemented to check for change in signal state. The results were then filtered according to the output of the formula, and the zero-time converted timestamps were copied alongside the signal state tags. The time delta was then extracted by subtracting a previous time from the current of each row. Finally, appropriate tags regarding the types of actuators -, direction-, measurement cycles-, and pistons used were added. The data was then combined into one large table to be exported to IBM SPSS for further analysis.

	A	B	C	D	E
1	T	D	C	P	TIME
2	0	0	0	0	216,0901
3	0	0	0	0	217,1799
4	0	0	0	0	217,4001
5	0	0	0	0	217,8098
6	0	0	0	0	216,03
7	0	0	0	0	215,9299

Figure 4. Fully managed data with tags

2.3 Actuator description

Figure 5. 5/2-way single solenoid valve (Festo 167074)

Figure 6. 5/2-way double solenoid valve (Festo 539778)

Two different types of actuators were used in the measurements, one being asymmetric digital/mechanical and one being fully digital and symmetric. The asymmetric 5/2-way single solenoid valve (D:SPPVE-5/2-MEH-SB 167074 PD06), coined as mechanical, was selected to determine the effects of mechanical actuation on response time variability. The mechanical actuator consists of an electrically operated solenoid on one end and a spring return system on the other. When the solenoid is not active, the spring keeps the actuator in its initial state. When the solenoid receives a signal, the valve inside of the actuator is moved, compressing the spring. When the signal is then lost, the compressed spring extends providing the return motion. The Festo datasheet for the valve claims a 20ms solenoid switching time and a 30ms spring switching time at 6 bar pressure. The symmetric 5/2-way double solenoid valve (D:TP-BG-VSVA-B52-Q4M8 539778 W906), coined as digital, consists of solenoids on each end of the actuator, moving the valve in response to a change in signal state. The Festo datasheet for the valve claims a 15ms switching time at 6 bar pressure.

Figure 7. Double acting cylinder (Festo 152888)

Two pistons were also used (Festo D:S-PAZ-DW20-100PPV 152888 R106, and - D:S-PAZ-DW20-100PPV 152888 WD06), coined as piston 1 and piston 2 respectively. Piston 1 seemed to be older than piston 2 and was therefore selected to represent wear in automation systems. Upon inspection, moving the piston head manually produced a more polyphonic sound of air escaping than in piston 2. This led the research to consider that air might be escaping from the cylinder in piston 1 in more locations than in piston 2. Upon moving the piston head to its maximum extension, the piston head moved more vertically than in the case of piston 2. At maximum extension the piston head in piston 1 moved approximately 2 mm whereas piston 2 about 1 mm. This was considered as a possible cause of response time variability, as more kinetic energy would be wasted on vertical movement instead of horizontal. Thirdly, the rubber seal on the extension side of piston 1 was more pushed out than that of piston 2. The Festo datasheet claims a thrust force of 189 N and a 158 N return force at 6 bar pressure.

2.4 Analysis environment and methods

To conduct the measurements, a trace configuration was installed onto the PLC via TIA Portal version 15. The trace measurement system has the capability of recording the activation state of tags in the TIA Portal tag table, the results of which can then be exported in different formats. For the purposes of the study, the output tags of the piston position were chosen. Additional configuration included using the maximum possible recording resolution of 52 000 samples and a rising edge trigger event on first extension motion. Both were done to acquire the most accurate results possible, as the number of samples determines the degree of differentiation in the results and the trigger ensures minimized downtime.

The gathered data was then exported in .csv format to Microsoft Excel. Despite the statistical analysis capabilities of Excel, IBM SPSS 26 was concluded to be the preferable option. Comparing the two, it can be said that both are capable of performing same types of analyses. However, the choice of automated analyses in Excel is very limited. The equations would have needed to be input manually. This was considered too unreliable, especially considering the complexity of the equations used. As SPSS is accessible to students and contains automated procedures for running the analyses and was therefore selected.

A number of different analyses were made in SPSS, with the generic “data explore” being the most common. The function produced the descriptive statistics, histograms, and box-plots, which can be seen in chapters 3 - 4. To determine the statistical significance of the findings, a wide array of methods was implemented. The most effective ones were determined to be independent sample T-test and multivariable correlation. The independent sample T-test was chosen as it allows for a control measure for time. The T-tests measure variability between means, and as the categories without the control are nominal, the differences measured would have been the differences in means between the tag states 0 and 1. Multivariable correlation was chosen to provide a single table of correlations. This simplified the comparison to a useful degree. Multivariable correlation also allowed for a time control to be inserted as well, which simplified the table further.

2.5 Null hypothesis

Having gathered all the relevant information, a null hypothesis was formed. Due to the extensive wear on piston 1, it was hypothesized that piston 2 would outperform it in every circumstance. The data gained from the Festo datasheet seemed to indicate that the return motion would be somewhat slower, but the magnitude of the difference seemed to point to rather small difference. As for the valves, it was hypothesized that the mechanical actuator would prove to be more variable in terms of response time due to the spring return system. The data gained from the Festo datasheet for both valves seemed to indicate that the digital actuator would outperform the mechanical. Additionally, the data seemed to indicate that the slowest switching time was the mechanical return on the mechanical actuator.

The null hypothesis was therefore set as follows: the actuation response time will primarily depend on the actuator used, with some lesser effect produced by the piston used. The retraction motion using piston 1 in conjunction with the mechanical actuator will be the highest significant outlier in terms of absolute response time, where-as either motion using piston 2 in conjunction with the digital actuator will be the lowest significant outlier in terms of absolute response time. Furthermore, the mechanical actuator will produce the most variable results.

3 Data by properties

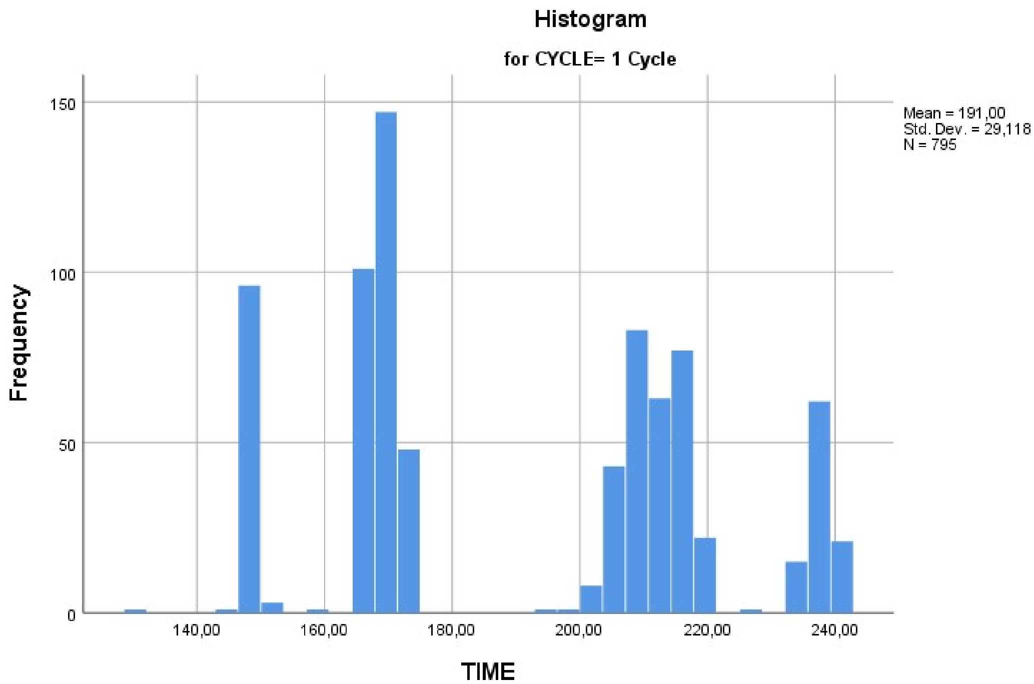


Figure 8. Histogram for 1-cycle measurement

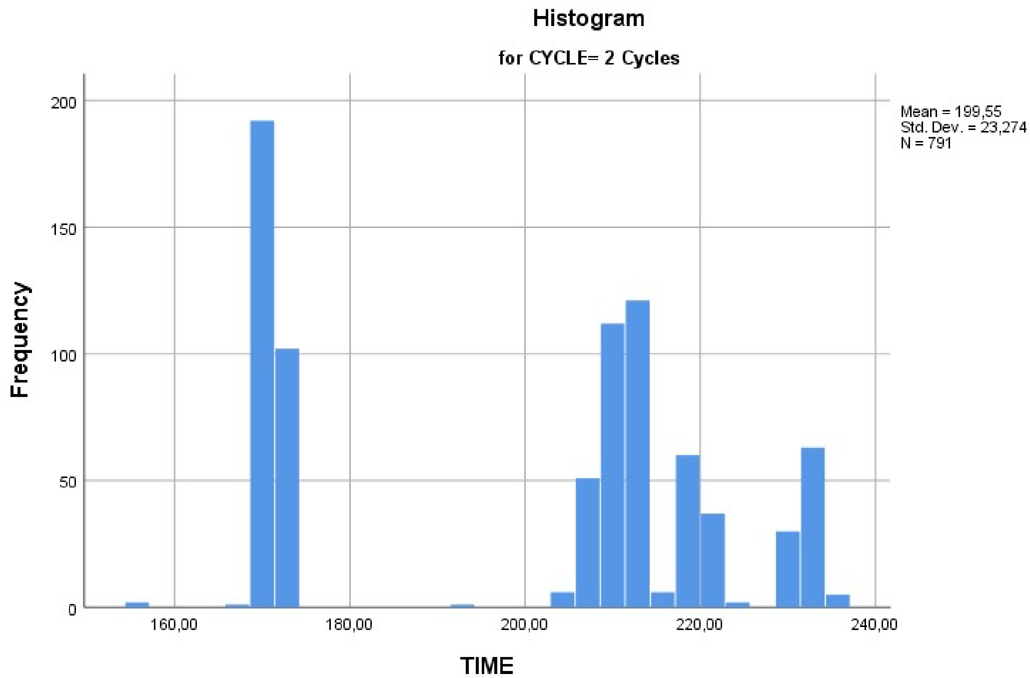


Figure 9. Histogram for 2-cycle measurement

To verify the data, two measurements were taken: one measurement every cycle of the program, and one every other cycle. Visible in Figures 8 and 9 are the histograms produced in SPSS regarding the cycle type. Viewing the histograms, one can see that the results for 1-cycle measurements are more differentiated than those of 2-cycle measurements. This is especially apparent in the minimum response times displayed in both. It seems that the 2-cycle measurement method collapsed a fairly large portion of the absolute minimum, at approximately 150ms in Figure 8, into a larger peak around 170ms in Figure 9. Comparing the frequencies of the instances, one can also see that the total number of frequencies in the lower end of the spectrum are approximately 300 in both cases. This confirms that the values were collapsed into the larger minimum peak in Figure 9, and as such, the 1-cycle measurement method was deemed to be the maximum possible resolution for the measurements. The rest of the study was therefore conducted using only the data gained from the 1-cycle measurements.

Viewing Figure 8, one can roughly categorize the data according to the peaks produced, namely: around 150ms, -170ms, -210ms, and -240ms. Starting from the null hypothesis, it was theorized that the lower end of the spectrum would be coincident with the use of piston 2 and the digital actuator. In accordance to the null hypothesize, it was assumed that the higher end of the spectrum would coincide with piston 1 and the mechanical actuator, and the lower with piston 2 and the digital actuator.

3.1 Results in terms of pistons used

Descriptives[a]

	PISTON			Statistic	Std. Error
TIME	Piston 1	Mean		207,8296	1,22564
		95% Confidence Interval for Mean	Lower Bound	205,4200	
			Upper Bound	210,2391	
		5% Trimmed Mean		208,2603	
		Median		212,9099	
		Variance		597,875	
		Std. Deviation		24,45149	
		Minimum		147,82	
		Maximum		241,22	
		Range		93,40	
		Interquartile Range		47,66	
		Skewness		-,456	,122
		Kurtosis		-,994	,244
	Piston 2	Mean		174,1286	1,15611
		95% Confidence Interval for Mean	Lower Bound	171,8557	
			Upper Bound	176,4015	
		5% Trimmed Mean		173,5785	
		Median		167,3401	
		Variance		530,626	
		Std. Deviation		23,03532	
		Minimum		131,67	
		Maximum		213,07	
		Range		81,40	
		Interquartile Range		47,28	
		Skewness		,637	,122
		Kurtosis		-,913	,244

a. CYCLE = 1 Cycle

Figure 10. Descriptive statistics for pistons used

In accordance with the null hypothesis, the descriptive statistics in Figure 5 do indeed show that both the mean and the median response times are lower when piston 2 was deployed.

The skewness of the data is also reversed between the two, where piston 1 data tends to collect to the higher end of the spectrum with skewness of -0,599 and the piston 2 data tends to the lower with skewness of 0,193. Kurtosis of both pistons tend toward the same direction however, with piston 2 exhibiting lower kurtosis of -1,44 in contrast to that of piston 1 at -0,952. This would seem to indicate that piston 2 would produce more variable results. In terms of range and interquartile range, the two pistons perform quite similarly to one another, and despite the different means and medians, the actuation times are likely to overlap.

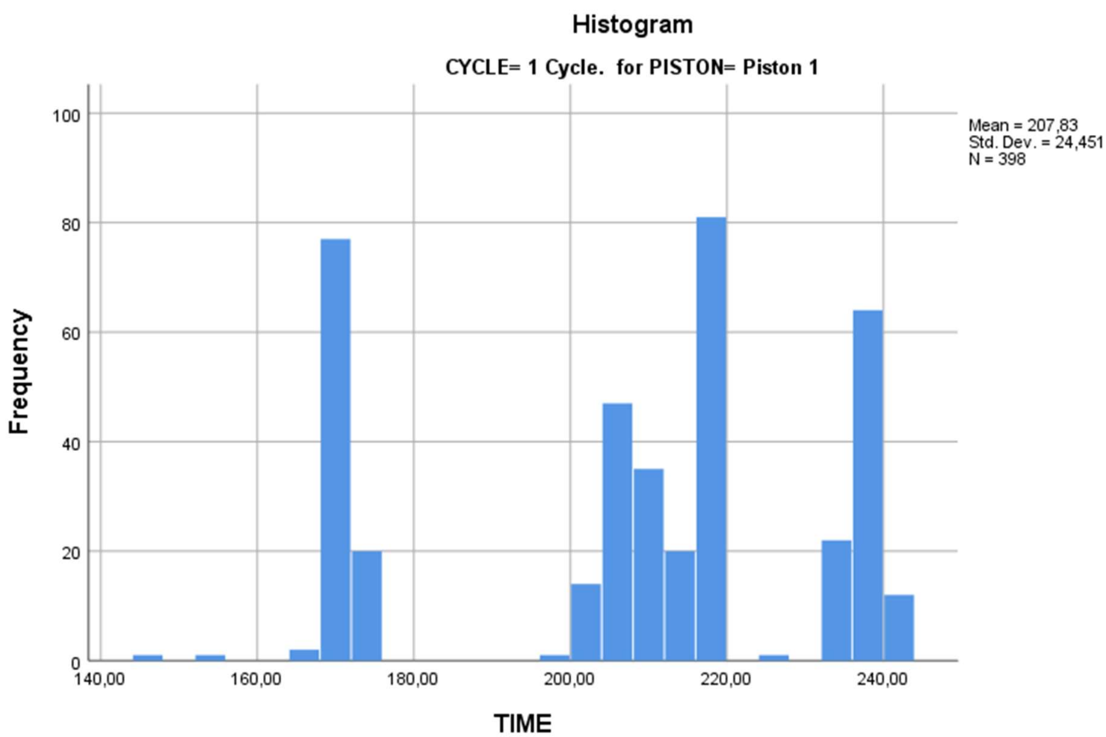


Figure 11. Histogram for piston 1

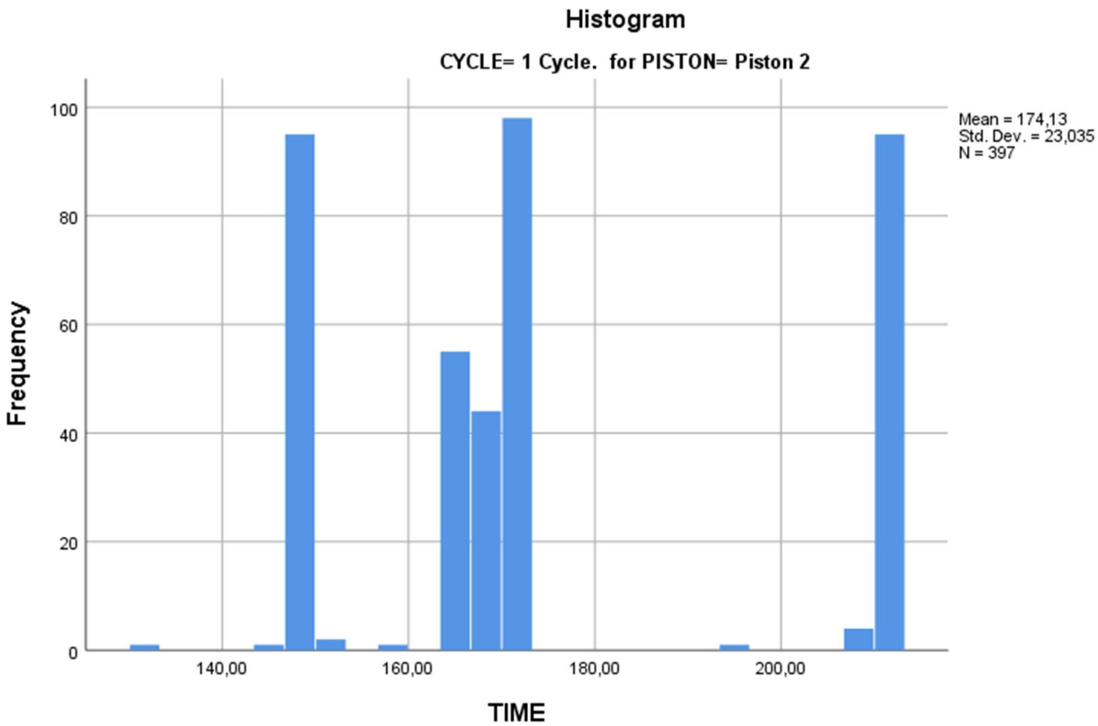


Figure 12. Histogram for piston 2

Visible in Figures 11 and 12 is a decomposition of the 4-peak structure seen in Figure 8, in which the use of different pistons produces a split in the data, which in turn forms a 3-peak structure, encompassing the higher - and lower ends of the spectrum respectively. Despite a few instances of 150ms response times in Figure 11, the vast majority of 150ms instances seem to correspond with the use of piston 2. This would seem to corroborate the findings made about the physical states of the pistons, where it was hypothesized that piston 2 would outperform piston 1.

Contradicting the previously made assertion regarding the variability of the results, it would seem that piston 2 would indeed produce more disparate results in comparison to piston 1. However, viewing Figure 11 one can see that at the higher end of the spectrum, the actuation time grouping is spread more widely than any grouping visible in Figure 12. This would seem to indicate that the use of piston 2 would indeed produce more varied results in reference to itself, but relative to the grouping of the instances, piston 1 would seem to produce more variable results.

The histograms would seem to point to a significant overlap in both use cases. The overlap however is limited to the middle cases of the total data described in Figure 3, which are the minimum and maximum cases in Figures 6 and 7 respectively. Despite the overlap, the absolute minimum and maximum cases do not overlap in either of the Figures and seem to point to a somewhat significant difference caused by the use of either piston.

3.2 Results in terms of actuators used

Descriptives[a]

	TYPE			Statistic	Std. Error
TIME	Mechanical	Mean		209,0890	1,21108
		95% Confidence Interval for Mean	Lower Bound	206,7080	
			Upper Bound	211,4699	
		5% Trimmed Mean		209,5086	
		Median		213,0698	
		Variance		582,288	
		Std. Deviation		24,13065	
		Minimum		167,00	
		Maximum		241,22	
		Range		74,22	
		Interquartile Range		39,42	
		Skewness		-,563	,122
		Kurtosis		-,947	,244
	Digital	Mean		172,9571	1,07666
		95% Confidence Interval for Mean	Lower Bound	170,8404	
			Upper Bound	175,0737	
		5% Trimmed Mean		172,3623	
		Median		167,3099	
		Variance		461,356	
		Std. Deviation		21,47921	
		Minimum		131,67	
		Maximum		212,91	
		Range		81,24	
		Interquartile Range		29,69	
		Skewness		,583	,122
		Kurtosis		-,889	,244

a. CYCLE = 1 Cycle

Figure 13. Descriptive statistics for actuator used

Viewing the data presented in Figure 13, the null hypothesis seems to be somewhat corroborated, as the digital actuator produces an approximate 10% lower variance and a significantly lower mean response time. This is somewhat curtailed by similarities of range and interquartile range in both cases. The data would seem to indicate that the mechanical actuator does not seem to be related to the previously discovered 150 ms actuation time peak, as the absolute minimum of the data goes only as low as 167 ms. Contrasting this with the absolute maximum of the mechanical -, and that of the digital actuator, it would seem that a similar pattern as described with regards to piston use takes shape. The skewness and kurtosis data seem to mirror this as well, with the skewness changing direction as in Figure 5, and the kurtosis diminishing in a similar manner.

The -0.675 skewness of the mechanical actuator data would seem to point to a high-end weighted data in comparison to the 0.177 skewness of digital actuator data. The -0.916 kurtosis of the mechanical actuator data would seem to point to a more diffuse spread in comparison to the -1.382 kurtosis of the digital actuator data.

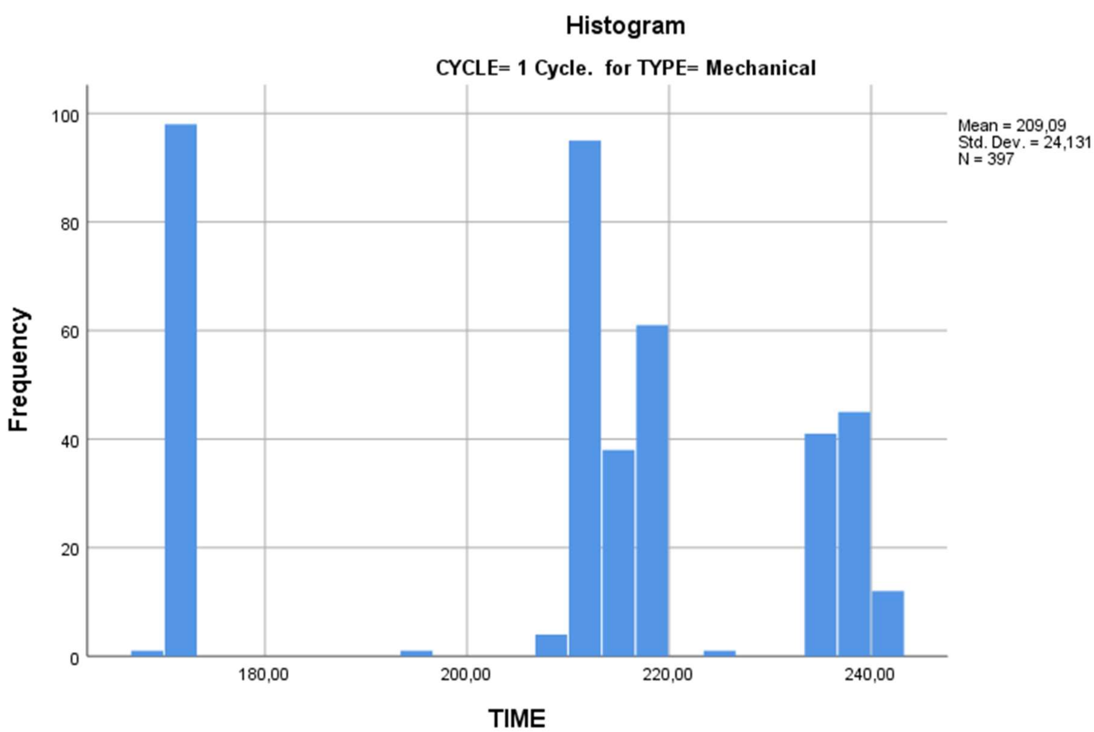


Figure 14. Histogram for mechanical actuator

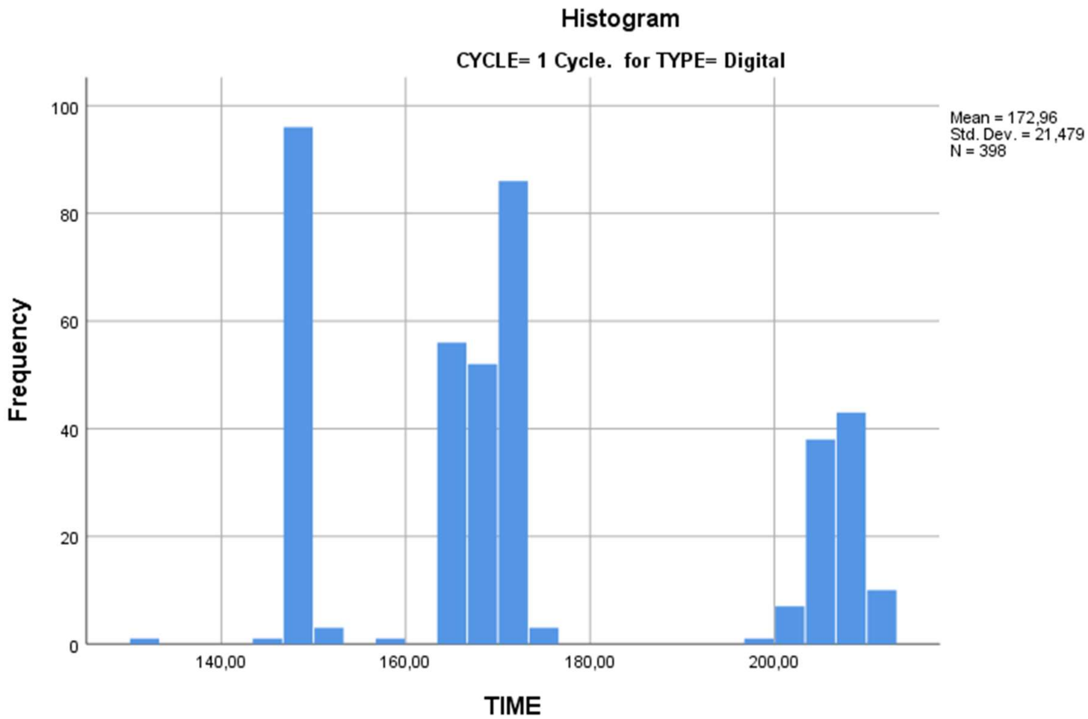


Figure 15. Histogram for digital actuator

Similar to the histograms presented in Figures 11 and 12, the histograms in Figures 14 and 15 decompose the 4-peak pattern in Figure 8 into 3 separate peaks. A similar pattern emerges as described above, where the middle value of the complete data presented in Figure 3 are present in both histograms, whereas the absolute minimum and maximum actuation times are split by the type of actuator used. Viewing Figure 14, one can see that indeed no 150 ms are present in the histogram. A significant peak however can be seen in Figure 15. Contrasting these findings with regards to the low frequency instances of 150 ms presented in Figure 11, it can be assumed that if indeed the piston 1 did experience this actuation time minimum, it would have happened in conjunction with the use of the digital actuator. In contrast to the findings made in Figures 11 and 12, the use of different types of actuators would seem to produce a similar effect as with the pistons, where the use of the digital actuator is produces more variable results in reference to itself, but the use of the mechanical actuator would produce more variable results in terms of grouping.

4 Data by direction

4.1 Direction by actuator type

Descriptives[a]

	TYPE			Statistic	Std. Error
TIME	Mechanical	Mean		194,1590	1,63732
		95% Confidence Interval for Mean	Lower Bound	190,9302	
			Upper Bound	197,3879	
		5% Trimmed Mean		194,0975	
		Median		212,9099	
		Variance		533,480	
		Std. Deviation		23,09719	
		Minimum		167,00	
		Maximum		219,79	
		Range		52,79	
		Interquartile Range		46,05	
		Skewness		-,006	,172
		Kurtosis		-2,013	,343
	Digital	Mean		186,5033	1,43692
		95% Confidence Interval for Mean	Lower Bound	183,6698	
			Upper Bound	189,3369	
		5% Trimmed Mean		186,3438	
		Median		167,3351	
		Variance		412,949	
		Std. Deviation		20,32114	
		Minimum		159,06	
		Maximum		212,91	
		Range		53,85	
		Interquartile Range		40,41	
		Skewness		,041	,172
		Kurtosis		-1,982	,342

a. CYCLE = 1 Cycle, DIRECTION = Extension

Figure 16. Extension by actuator used descriptive statistics

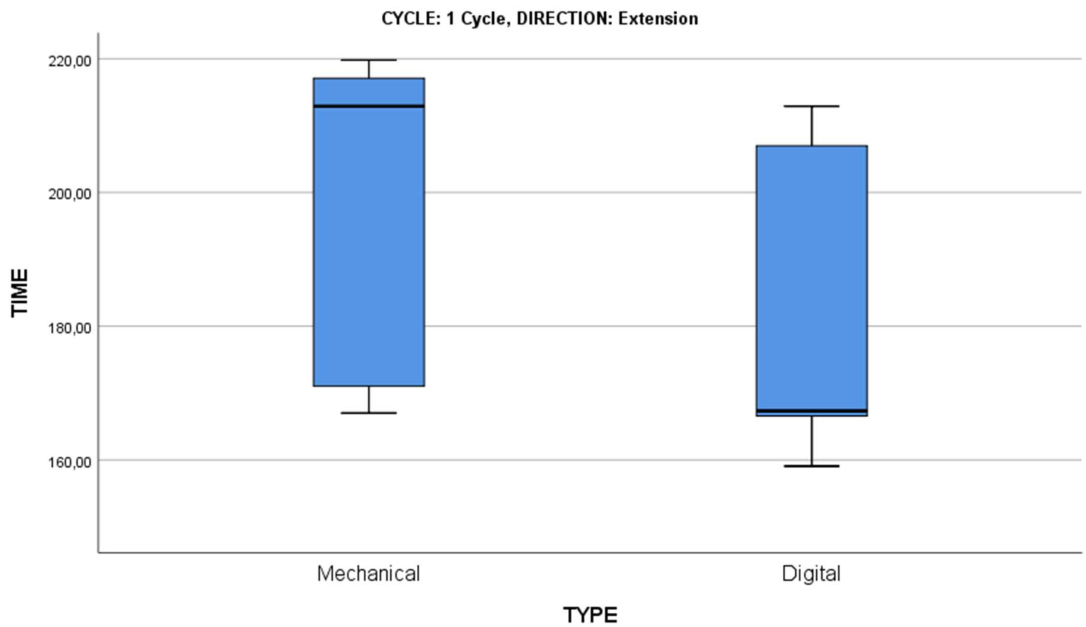


Figure 17. Extension by actuator used box plot

As stated in the null hypothesis, it was thought that the extension motion of the pistons using a mechanical actuator would be slower than that of the digital. This was due to the presence of the mechanical spring on the return side of the actuator. Viewing Figure 17 however, one can see that the Figures overlap to a large degree, with mechanical being only slightly higher. Viewing Figure 16, few differences can be seen, namely in kurtosis and skewness. It seems that although largely similar, the mechanical actuator does seem to produce more variable results, having a smaller kurtosis than the digital and approximately 20% higher variance than the digital. Additionally, looking at the median values of each, one can see that the digital actuator seems to cluster towards the lower end of the distribution, where-as the mechanical seems to cluster towards the higher end of the distribution.

Descriptives[a]

	TYPE			Statistic	Std. Error
TIME	Mechanical	Mean		224,0943	,96093
		95% Confidence Interval for Mean	Lower Bound	222,1993	
			Upper Bound	225,9893	
		5% Trimmed Mean		224,0394	
		Median		219,3248	
		Variance		182,832	
		Std. Deviation		13,52154	
		Minimum		194,53	
		Maximum		241,22	
		Range		46,69	
		Interquartile Range		26,57	
		Skewness		,000	,173
		Kurtosis		-1,900	,344
	Digital	Mean		159,2739	,83522
		95% Confidence Interval for Mean	Lower Bound	157,6268	
			Upper Bound	160,9211	
		5% Trimmed Mean		159,2701	
		Median		150,3600	
		Variance		138,123	
		Std. Deviation		11,75256	
		Minimum		131,67	
		Maximum		174,15	
		Range		42,48	
		Interquartile Range		23,05	
		Skewness		,000	,173
		Kurtosis		-1,884	,344

a. CYCLE = 1 Cycle, DIRECTION = Retraction

Figure 18. Retraction by actuator used descriptive statistics

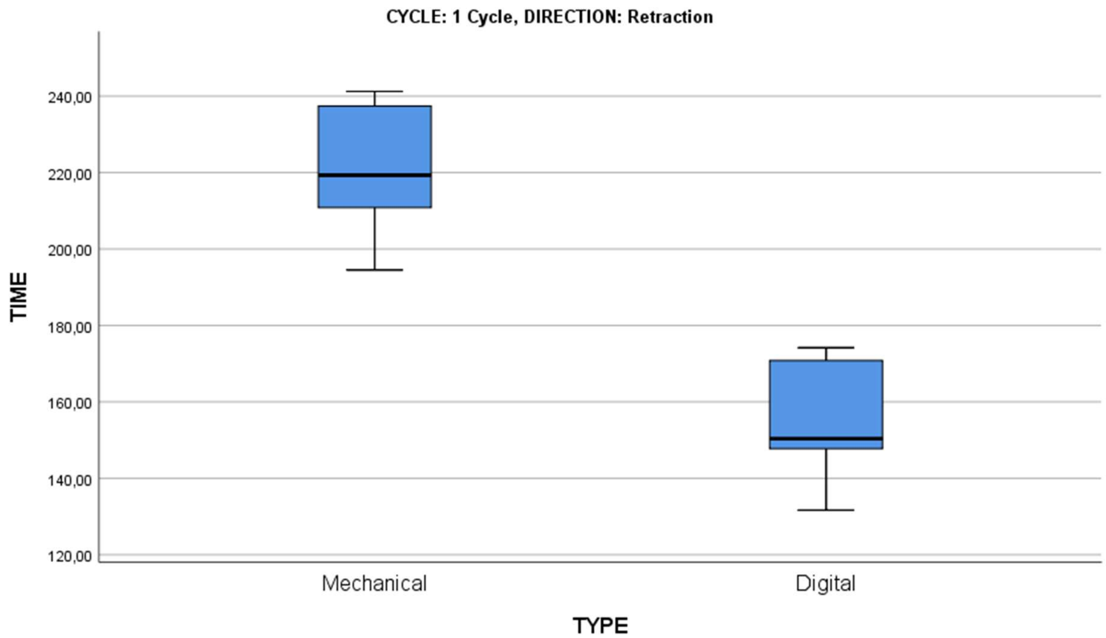


Figure 19. Retraction by actuator used box plot

Viewing Figure 19 a rather large difference between the actuators can be seen. It seems that in the retraction motion, the two actuators do not overlap in any case. This can be verified in Figure 18, where the maximum and the minimum response time of the digital and mechanical actuators respectively are separated by approximately 23 ms. The skewness seems to indicate a perfect centre normal distribution in both cases. The kurtoses of the two is very comparable being only 5% smaller in the mechanical. The interquartile range and the full range are also comparable. This seems to indicate a very similar spread of the data, in contradiction to the null hypothesis.

The digital retraction motion seems to correspond to a large degree to the 150 ms grouping discussed earlier, having a median value of 150,36 ms. The mechanical retraction seems to correspond to the spike observed around the 235 ms mark. This seems to point to the validity of the earlier made assumption based on the null hypothesis, where it was stated that the mechanical would be more associated with the higher end of the distribution, while the digital would be more so on the lower end of the distribution.

4.2 Direction by piston

Descriptives[a]

	PISTON			Statistic	Std. Error
TIME	Piston 1	Mean		211,5430	,50147
		95% Confidence Interval for Mean	Lower Bound	210,5541	
			Upper Bound	212,5318	
		5% Trimmed Mean		212,0183	
		Median		212,9099	
		Variance		50,294	
		Std. Deviation		7,09186	
		Minimum		166,44	
		Maximum		219,79	
		Range		53,35	
		Interquartile Range		10,14	
		Skewness		-2,545	,172
		Kurtosis		13,891	,342
	Piston 2	Mean		168,9936	,27834
		95% Confidence Interval for Mean	Lower Bound	168,4447	
			Upper Bound	169,5425	
		5% Trimmed Mean		168,8316	
		Median		167,3401	
		Variance		15,417	
		Std. Deviation		3,92650	
		Minimum		159,06	
		Maximum		212,91	
		Range		53,85	
		Interquartile Range		4,47	
		Skewness		7,008	,172
		Kurtosis		78,772	,343

a. CYCLE = 1 Cycle, DIRECTION = Extension

Figure 20. Descriptive statistics for extension by piston

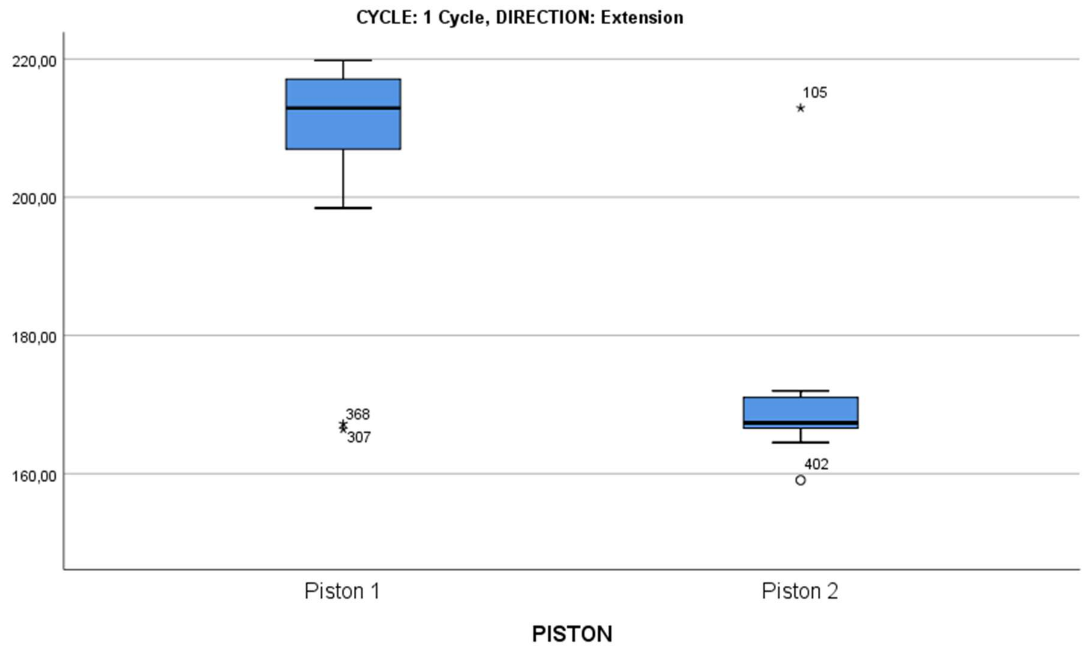


Figure 21. Extension by piston box plot

Viewing Figure 21 one can see that the extension motions of the two pistons do not overlap, except for a few extreme outliers. As can be seen in Figure 20, the kurtosis of the two are extremely high, pointing to a very consistent actuation pattern. The kurtosis for piston 2 is approximately 6 times larger than for piston 1, which seems to indicate to the validity of the null hypothesis regarding the variability of the results. The skewness points in different directions, favouring a more high-end distribution on piston 1 and a lower end on piston 2. The means of the two are separated by more than 43 ms, which seems to corroborate the null hypothesis regarding the performance difference between the pistons. Figures seem to point to the validity of the assumption made regarding the placement of the two pistons on the total distribution seen in Figure 8.

Three extreme outlier values can be seen in Figure 21, in piston 1 according to the minimum at 166,44ms labelled 368 and 307 and in piston 2 according to maximum at 212,91 ms labelled 105. Checking the individual data points in SPSS, it was determined that all of the extreme outliers were produced by the use of the digital actuator.

Descriptives[a]

	PISTON			Statistic	Std. Error
TIME	Piston 1	Mean		204,0787	2,38462
		95% Confidence Interval for Mean	Lower Bound	199,3760	
			Upper Bound	208,7813	
		5% Trimmed Mean		204,1695	
		Median		199,8649	
		Variance		1125,911	
		Std. Deviation		33,55459	
		Minimum		147,82	
		Maximum		241,22	
		Range		93,40	
		Interquartile Range		66,60	
		Skewness		-,010	,173
		Kurtosis		-1,984	,344
	Piston 2	Mean		179,2896	2,24479
		95% Confidence Interval for Mean	Lower Bound	174,8627	
			Upper Bound	183,7165	
		5% Trimmed Mean		179,3524	
		Median		172,6100	
		Variance		997,737	
		Std. Deviation		31,58698	
		Minimum		131,67	
		Maximum		213,07	
		Range		81,40	
		Interquartile Range		63,09	
		Skewness		-,002	,173
		Kurtosis		-2,007	,344

a. CYCLE = 1 Cycle, DIRECTION = Retraction

Figure 22. Descriptive statistics for retraction by piston

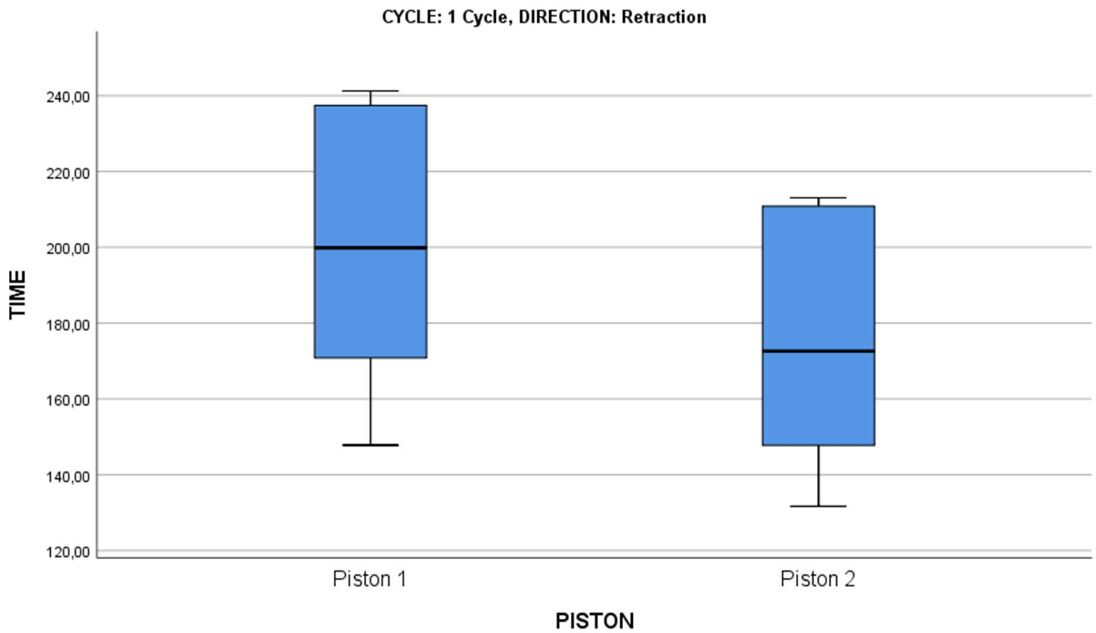


Figure 23. Retraction by piston box plot

The retraction motion for both pistons appear to be largely similar in Figure 23. The similarities in the size of the range, interquartile range and the kurtosis of the two seem to point to similar variability in between the pistons. This seems to be in contradiction to the null hypothesis, while the means of the pistons being separated by approximately 35 ms in accordance. The skewness of both seems to indicate a near perfect centre normal distribution.

Taking a general overview of the data gathered, it can be seen in Figures 19 and 21 that the type of actuator used seems to govern the variability of the actuation time in retraction, while the piston used seems to govern the variability in extension. Comparing Figures 19 and 23 it seems that the type of piston used does not seem to have a large time on the retraction. This seems to indicate that the effect of the switching times found in the Festo datasheets seems to be larger than was reported. The findings in Figures 17 and 21 call this to question however, seeing as despite the reported similarities between the two result in much wider distribution in Figure 17, while the pistons in Figure 21 create two very disparate and tight groupings. Looking at Figures 21 and 23 it seems that the difference in thrust – and return force seems to have a larger effect than was assumed by the null hypothesis.

5 Joining data with affecting factors

Having collected and catalogued the factors affecting response time, the combinations of the factors and their respective effects can be analysed. Using the total data pool visible in Figure 3, each of the peaks in data was decomposed into its constituent parts.

Starting at the low end, the absolute minimum instance can be found at around 130ms. Following through the line of inquiry presented in the previous chapters, the instances can be traced recurring in Figures 12, 15, and 19. Though it remains uncertain whether the result is accurate or an error, the 95% confidence interval in Figure 18 seems to point to an error. The elements causing the instance are the use of piston 2, digital actuator, going through a retraction motion.

The first major peak in the data, and the lowest replicable response time grouping sits around 150 ms. The peak can be seen recurring in Figures 11, 12, 15, 19, and 23. Visible in Figure 11, the frequency of the data point sits in the single digit range when using piston 1. Figures 12 and 23 seems to prove that the use of piston 2 would be more predictive of the specified response time grouping. Viewing Figures 14 and 15 it can be deduced that the phenomena can only be produced by the digital actuator. In Figures 19, 21, and 23 the predictive element of this phenomena seems to be the retraction motion. The elements therefore can be summarized as the retraction motion using the digital actuator, with the majority occurring when using piston 2, but possible when using piston 1.

The second major data peak, situated around 170 ms in Figure 8, can be seen in almost every measure and split conducted. The only exceptions to this can be seen in Figure 19, where the mechanical actuators retraction motion does not seem to be capable of producing the phenomena. Viewing Figure 1, it seems that the extension motion of piston 2 seems to be a very good predictor of the actuation time, with piston 1 having only a few extreme outliers in the specified timeframe. Looking at the frequencies in Figures 12 and 13 around this timeframe seems to indicate that the effect is approximately times more pronounced on piston 2. The frequencies displayed in Figures 14 and 15 would seem to indicate that the effect would be similarly more prevalent in digital actuation as well. The effect can thus be summarized as a possible outcome of using either of the pistons or actuators and either direction, but approximately 2 times more prevalent in the case of piston 2 and less likely in extension. Using a digital actuator going through a retraction motion is the best predictor, with retraction on piston 1 being the least likely.

The largest single collection of frequencies and the second highest actuation time peak in Figure 8 sits around 210ms, extending approximately 10ms in each direction. The peak is the quite prevalent across all measurement instances, appearing in many of the Figures presented. Few notable exceptions to are the retraction motion using a digital actuator visible in Figure 19 and the extreme outlier presented in Figure 21. Viewing the frequencies in Figures 11 and 12, the majority of the instances in this timeframe can be seen to be more associated with the use of piston 1. The frequencies in Figures 14 and 15 seem to point to the fact that the use of a mechanical actuator would be more predictive of this time frame as well. Additionally, the specified timeframe seems to be the maximum possible for the digital actuator. The interaction can be therefore summarized as a possible outcome of the use of any of the pistons or actuators, but more likely in the case of piston 1 and mechanical actuator, with the exception of retraction motion caused by the digital actuator.

The final peak containing the absolute maximum response time of the study can be seen at around 235ms in Figure 8. Viewing Figures 11 and 12, the instance is solely visible in the use of piston 1. Additionally, the peak cannot be observed in Figure 15, indicating that it can only be produced by the use of the mechanical actuator. In terms of direction, the effect can be seen in Figures 19 and 23, relating to retraction motion of the mechanical actuator and piston using 1. The effect can therefore be summarized as the product of using piston 1, mechanical actuator and going through a retraction motion.

In trying to determine the statistical significance of the findings, a log-linear analysis was conducted. Although no significance was possible to extract from the analysis, a set of coefficients was discovered, which represent the percentage change per unit in dependent variable (time) separated by tag change of the coefficients.

Coefficients[b,c]

TYPE	DIRECTION	PISTON	TIME[a]
Mechanical	Extension	Piston 1	219,84
		Piston 2	170,56
	Retraction	Piston 1	231,91
		Piston 2	211,39
Digital	Extension	Piston 1	210,27
		Piston 2	210,38
	Retraction	Piston 1	171,14
		Piston 2	171,02

Figure 24. Log-linear coefficients

Visible in Figure 24 are generalized log odds as coefficients. Contrasting the numbers in Figure 24 to the histogram in Figure 8, one can find some similarities. The values presented roughly correspond to the peak presented in Figure 8, apart from the 150 ms grouping. This is explained by the relatively low frequency of the grouping. A general pattern can be observed in Figure 24, where it seems that the mechanical retraction motion is generally slower than the extension, and that piston 1 outperforms piston 2. This is most evident in mechanical extension, where piston 2’s coefficient is approximately 49 ms lower, whereas in mechanical retraction the difference is approximately 20 ms. Looking at the digital bracket, the extension seems to be approximately 39 ms slower than the retraction. Contrasting the two actuator types, the mechanical generally seems to actuate slower than the digital, except for extension of piston 2. The mechanical seems to outperform the digital by approximately 40 ms.

Looking at the general patterns, it appears that the null hypothesis was correct in assuming that the digital actuator and piston 2 would outperform the mechanical actuator and piston 1. A notable exception to this is the extension motion of piston 2 using the mechanical actuator. The coefficient seems to be lower than the previously discovered minimum of piston 2 retraction using the digital actuator. It would appear that despite having the absolute lowest possible response time, the mechanical extension seems to produce lower response time on average than the digital retraction.

Regarding the findings made in the Festo datasheets, the switching times presented seem to be somewhat predictive. The switching time for the digital actuator was reported as 15 ms in either direction. Looking at the coefficients in the digital bracket however, it would seem that although the pistons performed similarly to one another, the direction of the actuation produced an approximate 39 ms difference in response time. The mechanical actuator was reported to have a switching time of 20 ms on the solenoid side and a 30ms switching time on the spring return side. The claim seems to be accurate in relation to piston 2, where the retraction motion is indeed approximately 12 ms slower. The data regarding piston 2 however seems wildly inconsistent. Considering the difference in switching time, piston 2 produces an approximately 31 ms slower response time than expected.

6 Significance

6.1 Independent sample T-tests

Group Statistics[a]

	PISTON	N	Mean	Std. Deviation	Std. Error Mean
TIME	Piston 1	398	207,8296	24,45149	1,22564
	Piston 2	397	174,1286	23,03532	1,15611

a. CYCLE = 1 Cycle

Figure 25. Group statistics by piston

Independent Samples Test[a]

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TIME	Equal variances assumed	1,449	,229	20,001	793	,000	33,70096	1,68500	30,39338	37,00854
	Equal variances not assumed			20,002	790,425	,000	33,70096	1,68487	30,39361	37,00831

a. CYCLE = 1 Cycle

Figure 26. Independent samples T-test by piston

Using independent sample T-tests, the variance in means of two groupings can be compared. Depicted in Figures 25 and 26 are the tests run by grouping of the two pistons used. As can be seen in Figure 25 the means of the two pistons are quite different, where-as the standard deviation is quite close. Looking at Figure 26, the mean difference returns as 33,7ms. Contrasting this to the null hypothesis, it can be determined that the assumption that piston 2 would outperform piston 1 was accurate, but the assertion that piston 1 would produce more variable results can be considered questionable.

Looking at the Levene's test for equality of variance depicted in Figure 26, the significance returns as 0,229 when assuming equal variances. Proceeding on the first line, which is equal variances assumed, one can see in Figure 26 that despite the unequal means, the significance of the differences returns 0. This disproves the piston used as a statistically significant predictor of response time variance

Group Statistics[a]

	TYPE	N	Mean	Std. Deviation	Std. Error Mean
TIME	Mechanical	397	209,0890	24,13065	1,21108
	Digital	398	172,9571	21,47921	1,07666

a. CYCLE = 1 Cycle

Figure 27. Group statistics by actuator type

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TIME	Equal variances assumed	4,728	,030	22,300	793	,000	36,13191	1,62023	32,95146	39,31235
	Equal variances not assumed			22,297	782,041	,000	36,13191	1,62047	32,95093	39,31288

a. CYCLE = 1 Cycle

Figure 28. Independent samples T-test by actuator type

Viewing Figure 27, one can see that the means once are once again quite different and that the standard deviations appear quite similar. Looking at Figure 28, the mean difference returns as 36,1ms. This seems to indicate that as seen in Figure 26, piston 2 would outperform piston 1 to approximately the same degree as the digital actuator in comparison to the mechanical. Although the prediction presented in the null hypothesis regarding performance seems to be consistent with the observation, the assumed magnitude was larger than expected. Additionally, the assertion made regarding the larger variability of the mechanical actuator seems to be at least somewhat accurate.

Looking at Figure 23, one can see that the Levene's test for equality of variance returns a significance value of 0,03, which is below the set baseline of 0,05. Following the equal variances not assumed line, the significance returns as 0. This disproves the actuator type used as a statistically significant predictor of response time variance.

Group Statistics[a]

	DIRECTION	N	Mean	Std. Deviation	Std. Error Mean
TIME	Extension	399	190,3216	22,05818	1,10429
	Retraction	396	191,6841	34,83030	1,75029

a. CYCLE = 1 Cycle

Figure 29. Group statistics by direction

		Levene's Test for Equality of Variances		t-test for Equality of Means						
									95% Confidence Interval of the Difference	
		F	Sig.	t	df	Sig. (2-tailed)	Mean Difference	Std. Error Difference	Lower	Upper
TIME	Equal variances assumed	260,783	,000	-,659	793	,510	-1,36251	2,06619	-5,41837	2,69334
	Equal variances not assumed			-,658	667,142	,511	-1,36251	2,06953	-5,42610	2,70107

a. CYCLE = 1 Cycle

Figure 30. Independent samples T-test by direction

Looking at Figure 24, one can see that although the means are quite similar, the mean difference being according to Figure 30 approximately -1,3ms, the standard deviation of the two directions seem to differ a notable amount. Looking at Figure 29, the Levene's test for equal variances returns a significance of 0. Following the equal variances not assumed line, the significance of the direction of actuation comes to 0,51. As this is larger than the 0,05 set as a baseline, it is enough to prove the direction of the actuation to be a statistically significant predictor of response time variance.

6.2 Correlations

Paired Samples Correlations[a]

		N	Correlation	Sig.
Pair 1	TYPE & TIME	795	-,621	,000
Pair 2	DIRECTION & TIME	795	,023	,510
Pair 3	PISTON & TIME	795	-,579	,000

Figure 31. Paired samples correlation

A paired sample T-test was run to determine the correlation between time and type of actuator used, direction, and piston. As can be seen in Figure 26, the type and piston analyses returned a zero-significance value, while direction returned a significance value of 0,51. This corroborates findings made in the independent sample T-tests. The correlation however is very small, measuring only at 0,023.

Although the test was run on nominal factors, the results are still readable, with 0 being retraction, and 1 being extension. This would seem to indicate that extension is slightly more represented in the higher end of the spectrum at a significant rate as the correlation tends towards the positive. Conversely, it seems that the digital actuator and piston 2, both labelled 0, seem to be largely underrepresented at the higher end of the distribution, though at a statistically insignificant rate.

Correlations[a]

Control Variables			TYPE	DIRECTION	PISTON
TIME	TYPE	Correlation	1,000	,017	-,560
		Significance (2-tailed)	.	,634	,000
		df	0	792	792
	DIRECTION	Correlation	,017	1,000	,018
		Significance (2-tailed)	,634	.	,609
		df	792	0	792
	PISTON	Correlation	-,560	,018	1,000
		Significance (2-tailed)	,000	,609	.
		df	792	792	0

Figure 32. Correlations controlling for time of actuator type, direction and piston used

To verify this, a multi-variable correlation test was run. Looking at the direction variable presented in Figure 32, one can see that although seemingly insignificant independently, the use of either piston and the type of actuator do in fact play a measurably significant role, when considered as composite elements of the causes in response time extension regarding actuation direction. Both the type of actuator and the piston used have slight positive correlations of 0,017 and 0,018 respectively, and both have rather large significance values of 0,634 and 0,609 respectively. The values seem to point to the fact that the direction of the motion has a minor correlation regarding actuation time, of which the type of actuator and piston both have similarly minor correlation within the said frame. Considering the inverse correlation depicted in Figure 31, it can be read that the correlation in Figure 32 is predictive of underrepresentation of piston 2 and the digital actuator at higher ends of the distribution.

7 Conclusion and discussion of findings

Having gathered all the data, the veracity of the null hypothesis can be assessed. Stating originally that the primary elements affecting response time variability would be the piston - and the type of actuator used can be considered disproven. As determined in the significance analysis, the single factor with predictive power was the direction of the actuation. However, as was stated in chapter 21, both the actuator and piston used seem to have a slight positive correlation with rather large significance values and can be interpreted as constituent elements causing the variability caused by the direction of actuation. Contrasting this with the findings made in chapter 5, the null hypothesis can be re-interpreted in this framework.

The claim that the major cause of the highest actuation time being the retraction motion using piston 1 and the mechanical actuator can be seen as partially proven. As was established in chapter 5, the lowest possible actuation time is the result of piston 1 using the mechanical actuator going through a retraction motion. In addition to the findings in chapter 2, speculation as to the cause concluded that the mechanical spring in conjunction with the slightly pushed out seal on the piston, and the larger vertical movement of the piston head in its extended state were considered the most likely causes.

The claim that the cause of the lowest actuation time being either of the motions using piston 2 and the digital actuator can be considered partially disproven as well. As was determined in the significance analysis, the direction of the motion was the primary element determining response time difference. This can be seen most evidently in Figures 11 and 12, where the means of the motions using the digital actuator are separated from the mechanical by approximately 30ms. The switching time established by the Festo datasheet leaves 15ms of the difference unexplained. As established in chapter 5, the lowest possible actuation time is the result of piston 2 using the digital actuator going through a retraction motion. Some speculation was made regarding the cause of the phenomena, concluding that despite the identical switching time established in the valve datasheet, the difference in thrust – and return force of the pistons played a more significant role than expected.

The claim made regarding the effect of the piston used on runtime can be considered verified, as can be seen in Figure 13 and 14. Piston 2 seems to outperform piston 1 in almost every case, having a lower mean and extreme values than piston 2. Regarding the null hypothesis however, it was stated that the most variable results were expected to be using piston 1, in conjunction with the mechanical actuator going through a retraction motion.

However as can be seen in Figures 13 and 14 that regarding the piston used, the retraction motion produced more variable results. Contrasting this with the findings in Figures 11 and 12, the extension motion produced more variable results regarding the actuator type. Looking at Figures 5 and 8, one can see that the total variance is almost identical. The null hypothesis can be therefore considered disproven for the part in question and be corrected as follows: the variability of the actuation time is largely dependent on the direction of the motion, where the type of actuator used governs the variability in extension, and piston used in retraction. Variability can be therefore considered as a composite effect, yielding similar results though through different causes.

The Festo datasheets proved to be quite reliable. However, a notable inconsistency was discovered in the log-linear analysis, where the mechanical extension of piston 2 was much faster than was expected. The coefficient was found to be the lowest in the study, being lower than the lowest possible retraction motion on piston 2 using the digital actuator. The effect is well documented with a frequency of approximately a hundred repetitions and is to be considered valid. Considering the nature of the finding, it does not pose a significant contradiction to the earlier made data and effect pairing. The generalized log odds only point to a likely outcome of the combination of factors, meaning that despite not having the absolute lowest actuation time, it is the most likely in producing a lower response time than the other factors. The effect is notable however, as it contains the entire lower end peak visible in Figure 14.

Considering the approximate 150ms grouping as a verifiable minimum, a comparison can be made regarding the extension caused by digital effects as seen in Figure 2. The maximum extension caused by interrupting higher priority OBs without communication is 200%. Using the 150ms grouping as baseline and comparing it to the absolute maximum found in the study of 241,22ms, the extension caused by physical effects can be considered to be approximately 160%. Though no clear data is available as to the likelihood of the maximum extension regarding digital extension, considering the lower relative extension due to physical effects and the sparsity of the maximum response time instances, it can be concluded that the extension caused by digital effects can still be considered more significant of the two. However, the effect is only present when a higher priority OB interrupts the cyclic program, whereas the physical effects are consistently present. It can be therefore asserted, that although the absolute effect of digital effects remains the larger of the two, mechanical is the more persistent and pervasive.

As for the implications of the study, it can be concluded that the physical characteristics of actuators used are a statistically significant effect on runtime extension. Although less severe than the response time variability caused by digital means, the physical characteristics are somewhat unavoidable. Ideal circumstances for the most consistent runtime are therefore ones that minimize the amount physically effects. The most effective strategy for maintaining consistent response times can be summarized as: the use of digital actuators when possible, minimizing the amount of communication load and interruptions to the cyclic program, and the maintenance of the actuating device itself.

Considering future studies regarding the matter, the most effective strategy for determining the effect of variables on runtime was determined to be multivariate correlation analysis and log-linear analysis. Both are rather complex analyses, but trivial regarding modern computation capability. The former produces a clear-cut matrix, displaying the significant effects on runtime, which are then broken into its constituent parts. The latter can then be used to gain more insight as to the likely runtime groupings with regards to the combination of factors at play.

As computational power seems to be still increasing, the effect of physical characteristics persists until new innovations are made in actuator design. Although somewhat surface level, the study was able to come up with statistical means of determining the significance of various outwardly evident physical characteristics. The same procedures and methods can also be used on more subtle aspects of actuators, such as the effect of friction, mass, pressure etc. to gain more insight into the significant parameters of consideration in the design of actuators. This will allow for more data drive design in actuator design.

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