A METHOD TO MEASURING AND ANALYZING THE REACTION TIME OF AN INDUSTRIAL ETHERNET IO DEVICE

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Abstract: *The Real-time Industrial Ethernet IO system is a communication concept for implementing modular, distributed applications on the Ethernet. User data from the field devices are transmitted cyclically via a real-time industrial Ethernet channel to the process image of an automation control system. The reaction time of an IO device connected to the industrial Ethernet it is important in real-time systems. The paper presents an original and very efficient method to measuring and analyzing the reaction times of IO device driver channels. The described procedure was developed in LabView 8.2.*

Key words: *Ethernet, IO controller, Cycle time, Reaction time, Updates time*

1. Introduction

In process automation, a significant part of Industrial Ethernet system communication does not require time-synchronization between the control device and the field device drivers. From the point of view of communication, all devices have equal privileges on the Ethernet. During configuration a specific privilage level is assigned to each device, which defines the type and manner of communication according to the provider-consumer model [1].

In real-time systems control devices communication cycle usually is greater then *1 ms* and they control processes of varying speed, sometimes also considerably slow ones. Consequently, the system deadline is not of critical importance; in other words, the difference of a few milliseconds resulting from the lack of synchronization does not significantly alter the functioning of the system in real-time. For this reason the synchronization is not necessary, but is important to know the reaction time of IO devices [2-4], [7].

Under these considerations the paper is structured as follows: First the IO devices reaction time calculation is deduced and then based on the deduced formulas, a measuring method is proposed and presented. Based on the measurement method, for different measurement situations the obtained results are analyzed. At the end conclusions are presented.

2. Deduction of the Reaction Time Calculation

Consider an Industrial Ethernet System, illustrated in Fig. 1 with a single IO controller, a supervisor station and N amount of IO devices.

The IO controller station cyclically runs the user program and establishes a bidirectional communication relation with each IO device [10]. Label the cycle time of IO controller as T_C and the update times as U_{Tj} or U_{Tk}.

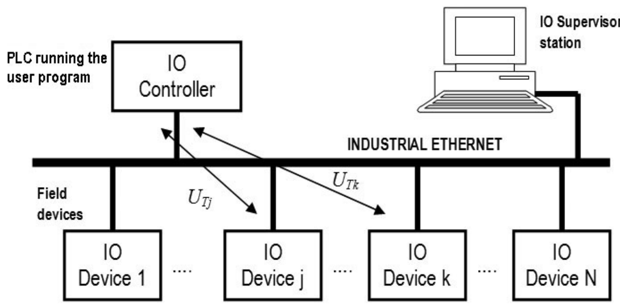

Fig. 1. Provider-Consumer Industrial Ethernet System

In the system depicted in Fig. 1, it is generally assumed that an output channel of the k^{th} device driver will respond due to a signal received by one input channel of the j^{th} device driver. Reaction time or response time is the time elapsed between the input excitation signal and the outgoing response.

The main factors determining this are the following:

- cycle time of IO controller (T_C),
- delay time of input channels (I_D),
- send time (S_T),
- update time (U_{Tj}, U_{Tk})

It is only the update time among the above listed determinants that can be defined in accordance with real time requirements. It should be further noted that it makes a difference at which point in time exactly the input signal is received relative to the cycle time and update time. Accordingly, response time will have a lower and an upper theoretical limit. In order to analyze the situation, these two extreme cases are to be determined.

The lower limit, the short response time (S_{RT}) presumes the preferred theoretical position; that is when the response arrives within a same IO controller cycle time. In this case, the response time depends only on the controller cycle time (T_C) and the input channel delay time (I_D) [7].

$$S_{RT} = T_C + I_D \quad (1)$$

This is the case when the input excitation signal comes within the actual send time and reaches the process image input (PII) just in time. Likewise, the response arrives in the most optimal send time when the process image output (PIO) of IO controller cycle time gets updated (Fig. 2) [7].

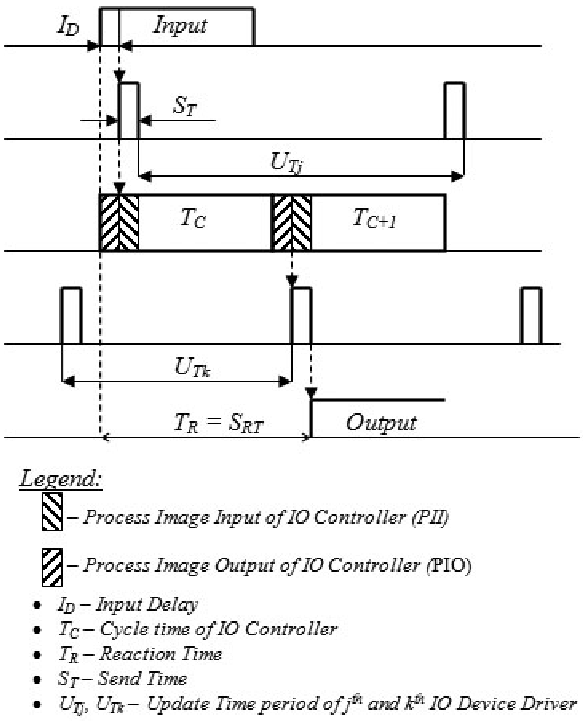

Fig. 2. Response time in the most preferable case

In the least preferable situation with the longest response time (L_{RT}), the incoming signal in the IO device input channel just misses the actual update time and subsequently, that of the process image input PII as well after the next update. As a result, it will only be loaded and executed in the following cycle time. Similarly, with regard to the response, the signal just misses the update time during the update of the process image output (PIO) [7]. As a result, it will be forwarded in the next cycle. This extreme case is illustrated in Fig. 3.

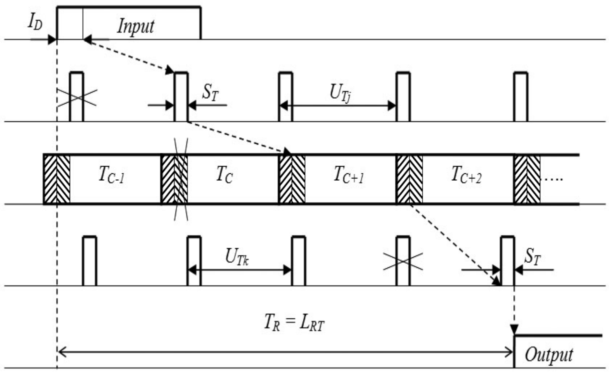

Fig. 3. The worst case response time

In general, according to the figure above, the response time value in the worst case can be established as it is in the following relation:

$$L_{RT} = I_D + U_{Tj} + 2 \cdot T_C + U_{Tk} + 2 \cdot S_T \quad (2)$$

It follows that the response time (T_R) will vary randomly between the two extreme cases defined with relations (1) and (2):

$$S_{RT} < T_R < L_{RT} \quad (3)$$

Or:

$$I_D + T_C < T_R < I_D + U_{Tj} + U_{Tk} + 2 \cdot (T_C + S_T) \quad (4)$$

The incidence of both extreme values is quite negligible, especially with configurations that have a higher value of update time.

The expected medium response time value can be calculated with the following formula:

$$T_{RM} = \frac{U_{Tj} + U_{Tk} + 3 \cdot T_C}{2} + I_D + S_T \quad (5)$$

Note: It makes little sense to set U_{Tj}, U_{Tk} update time values much lower than the value of the IO controller cycle time because in that case the reaction time will depend to a significant extent on the cycle time of the control device. Furthermore, the cycle time of the control device is very sensitive to the run-time of tasks caused by the interrupts.

The maximum value of jitter can be established with the following relation:

$$j_{max} = L_{RT} - S_{RT} = U_{Tj} + U_{Tk} + T_C + 2 \cdot S_T \qquad (6)$$

The percentage indicator of the relative deviation (ε_R) of the response time correlated the medium value can be further calculated as follows:

$$\varepsilon_R = \frac{j_{max}}{2 \cdot T_{RM}} = \frac{U_{Tj} + U_{Tk} + T_C + 2 \cdot S_T}{U_{Tj} + U_{Tk} + 3 \cdot T_C + 2 \cdot I_D + 2 \cdot S_T} .100\% \qquad (7)$$

The relations described above help to determine all factors necessary to provide a thorough description on how an industrial Ethernet IO system works in real-time.

3. Response time Measurement Methods

The application monitors and records measurement data provided by a National Instruments (NI) interface that is connected to the appropriate channels of the IO controller. This latter method has the great advantage that the measurement data can be collected in any desired amount and they can be evaluated and converted directly into an Excel spreadsheet.

The measurement is conducted by the NI Interface specifically designed for this purpose. The input/output signals are connected to the two counter inputs on the NI USB 6221 measuring unit [5]. The two inputs are configured to monitor the rising edges (Fig. 4).

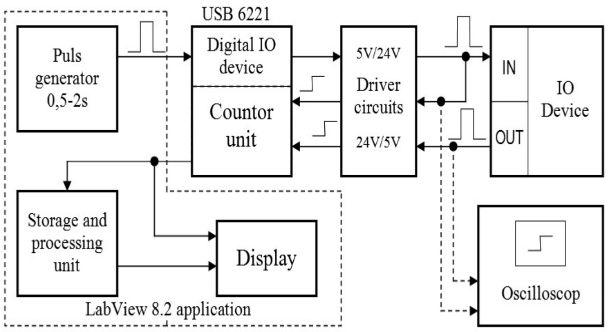

Fig. 4. Measurement concept using the NI interface

The counting is carried out in the time interval between two rising edges. The *0.05µs* measurement unit accuracy is guaranteed by the manufacturer [5].

Each data is stored in a one-dimensional array which can store several hundred or even thousand readings by default. The display always shows the current response time.

The input excitation between *0.5* and *2s* occurs with randomly generated pulses of *5V* amplitude and modifiable *10-500ms* width. The random procedure to generate pulses is necessary to obtain a more realistic model of any situation. These series of pulses are directed to one of the NI interface output channels, which are connected to the preferred IO device input channel.

The measurement is carried out in a fully automatic manner. Only the width of the measuring pulse size and the number of preferred samples must be specified. After the measurement has started, each result is immediately indicated and stored in the next record of the array.

Once the processing unit saved all the measurement results, it searches for extreme values (maximum and minimum), calculates the average, the jitter and the relative deviation. These will then also be saved, and to conclude, the processing unit converts the data into Excel format if the conversion option is enabled (Fig. 5).

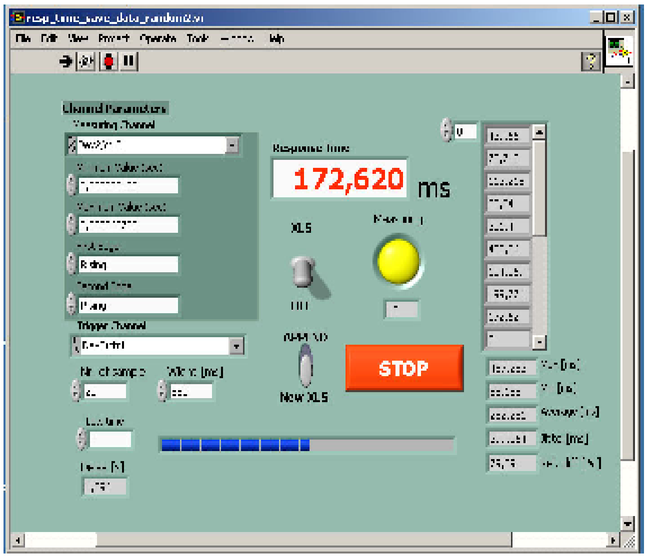

Fig. 5. LabView control panel and display interface

4. Some Particular Case Measurements Results

The subject of inquiry comprises a PROFINET IO system, which includes a S7-300 CPU315F-PN/DP PLC as IO controller, two ET-200 IM151-3 PN IO device drivers [6], a notebook as an IO supervisor and a SCALANCE X005 Ethernet switch (Fig. 6). Each device has a well-defined IP address.

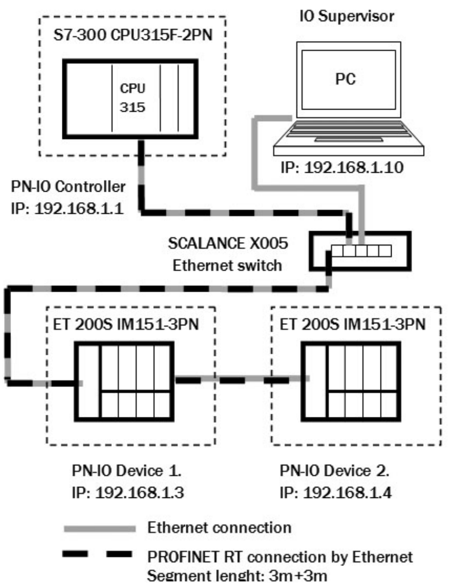

Fig. 6. Profinet IO test system including two IO Device drivers

In this paragraph, I have examined a particular situation in which both the excitation and the response occurs in IO channels belonging to the same IO device. In these cases relation (4), (5), (6) and (7) will become the following:

$$I_D + T_C < T_{Ri} < I_D + 2 \cdot (U_{Ti} + T_C + S_T) \qquad (8)$$

$$T_{RM} = I_D + U_{Ti} + S_T + \frac{3 \cdot T_C}{2} \qquad (9)$$

$$j_{max} = T_C + 2 \cdot (U_{Ti} + S_T) \qquad (10)$$

$$\varepsilon_R = \frac{T_C + 2 \cdot (U_T + S_T)}{3 \cdot T_C + 2 \cdot (I_D + U_T + S_T)} \cdot 100\% \qquad (11)$$

The obtained measurements and theoretical results are shown in the following table (Table 1).

Table 1. Typical reaction time values according to update times 1 to 32ms

Features [ms]	$I_D = 3ms$												$I_D = 0,5ms$	
	U_{T2} = 32ms		U_{T1} = 16ms		U_{T2} = 8ms		U_{T1} = 4ms		U_{T2} = 2ms		U_{T1} = 1ms		U_{T1} = 1ms	
	IO2-IO2	Theor.val	IO1-IO1	Theor.val	IO2-IO2	Theor.val	IO1-IO1	Theor.val	IO2-IO2	Theor.val	IO1-IO1	Theor.val	IO1-IO1	Theor.val
Max.	67.66	70.82	36.715	38.82	21.131	22.800	13.252	14.800	9.202	10.800	7.287	8.800	4.820	6.300
Min.	7.16	3.91	5.658	3.91	5.296	3.900	5.344	3.900	5.246	3.900	5.300	3.900	2.833	1.400
Med.	37.17	37.365	21.252	21.365	13.011	13.350	9.198	9.350	7.099	7.350	6.135	6.350	3.671	3.850
Jitter	60.50	66.91	31.057	34.91	13.842	18.900	7.908	10.900	3.956	6.900	1.987	4.900	1.987	4.900
ε_R [%]	81.39	89.54	73.07	81.70	60.88	70.79	42.99	58.29	27.86	46.94	16.19	38.58	27.06	63.64

The measurements were performed as per the update time values of *1, 4* and *16 ms* for first and *2, 8* and *32 ms* for the second IO device. The controller cycle time was T_C = *0.9 ms* (previously measured in [8]) and the send time was S_T = *1ms*. The test pulse width was set to *50ms* in order to provide a safe excitation in each case. The reaction times' characteristic values are included in the Table 1.

The specific time values of the preview table are based on 1000 reaction time measurements in each update time case.
The last two columns of the table show the most extreme case. Here the input delay time was reduced to *0.5ms,* while the update time of *1ms* was retained [9]. This represents a significant decrease in all characteristic values with the exception of the jitter. The grey columns include the theoretical values which have been determined by (2), (1), (9), (10) and (11) relations. The change of the measured response time values according to the update time is shown in Fig. 7.

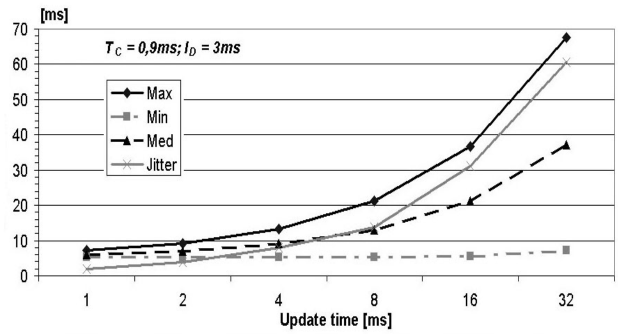

Fig. 7. Response time characteristic values

The minimal response time values in this case are nearly identical. They fall within the range of *5.2 – 5.7 ms* up until *16 ms* update time. Even at *32 ms* update time, they do not exceed *8 ms*. Therefore, the jitter follows the maximal value in nearly identical proportions, which is decisive so that the system may operate in real time. Knowing these values is very important for the configuration process of the system.

For example, if a system constrained by a deadline of *15 ms* is to be configured, the update time of the IO device will have to be set to *4 ms* maximum for an input delay of *3 ms*.

With regard to the distribution of the measured response time between the minimal and maximal values, it can be observed that a considerable part of the values fall close to the average. The changes are illustrated in Fig. 8. It is clear that increasing the update time period by 100% (from *16 ms* to *32 ms*) raises the distribution interval by the same proportion and reduces the percentage value of response times to 50%.

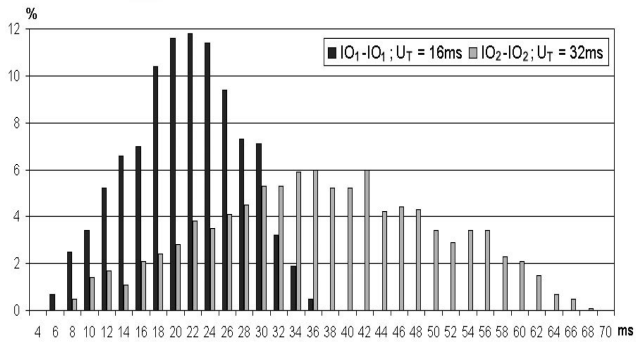

Fig. 8. Response time distribution change according to update time

5. General Case Study

In this section, the response time between two optionally configured IO devices will be the subject of analysis. The update time of the devices will vary in all cases. ($U_{Tj} \neq U_{Tk}; j = 1, k = 2$)

In this case, I calculated the theoretical response times using relations (4), (5), (6), (7) and measured these accordingly. For $U_{T1} = 16ms$ and $U_{T2} = 32ms$ Fig. 9 indicates the change in reaction times.

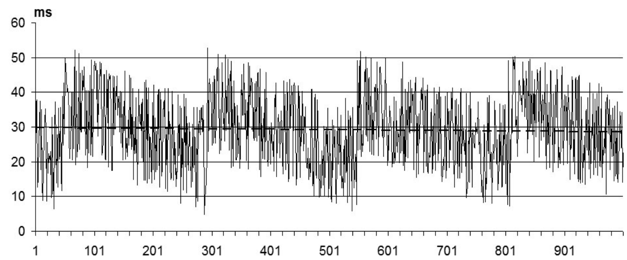

Fig. 9. Response time changes according to 16/32 ms update time

It is observable that the response time has a slightly decreasing tendency and sudden increases recurring at regular intervals. This can be explained by a lack of synchronization. The scenario shown on Fig. 3 occurs in the above described case: The input signal arrives at a point in time just missing one of the update times.

Further, it was analyzed whether there is a substantial difference between the various cases as the devices alternate the roles of provider and consumer. In order to do that, the test impulse is lead on into the input channel of IO_1. The response is received on the output channel of IO_2. Subsequently, IO_2 is excited and the response is received on IO_1. The cycle time of the control device remains *0.9ms,* the input delay 3*ms* and the update times are set to values $U_{T1} = 2, 16, 64, 256$ *ms* and $U_{T2} = 8, 32, 128, 512$ *ms* respectively. The results are presented in Table 2. The grey columns highlight the theory based calculations (presented in this paper).

Table 2. Two optionally configured IO deices reaction time features

Features [ms]	$U_{T1}/U_{T2} = 2/8ms$			$U_{T1}/U_{T2} = 16/32ms$			$U_{T1}/U_{T2} = 64/128ms$			$U_{T1}/U_{T2} = 256/512ms$		
	Measured		Theoretical values	Measured		Theoretical values	Measured		Theoretical values	Measured		Theoretical values
	IO_1-IO_2	IO_2-IO_1		IO_1-IO_2	IO_2-IO_1		IO_1-IO_2	IO_2-IO_1		IO_1-IO_2	IO_2-IO_1	
Maximum	15.176	15.303	16.8	51.53	52.765	54.8	193.744	191.847	198.8	709.187	767.402	774.8
Minimum	4.748	4.556	3.9	7.241	4.845	3.9	9.577	8.361	3.9	39.626	13.03	3.9
Average	10.103	9.891	10.35	28.892	29.284	29.35	100.877	97.650	101.35	377.365	378.681	388.95
Jitter	10.428	10.747	12.9	44.289	47.92	50.9	184.167	183.486	194.9	669.561	754.372	770.9
ε_R [%]	51.61%	54.33%	62.31	76.65	81.82	86.71	91.28%	93.95%	96.15	88.72%	99.61%	99.10

In all scenarios, the typical results shown in the table were arrived at following 1000 measurements. The excitation of the input channels occurred randomly at an interval of 0.5 and 1.5 seconds.

It should be noted how the distribution of response times changes when the roles of provider and consumer alternate between the devices. The values at the 2ms intervals show similar distributions in both cases (black and grey, Fig. 10). The largest difference (about 2.6%) can be observed between 24 and 26ms. At most intervals this value is typically below 1% or less. 90% of all cases fall within the range of ±16ms from the average (29ms, Table 2).

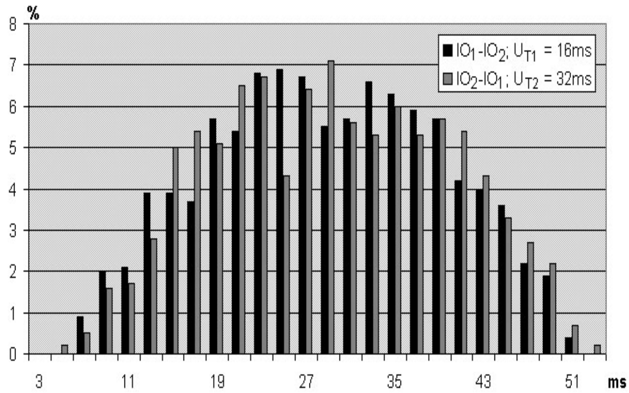

Fig. 10. Response time distribution change

6. Conclusions

Based on Table 1 and Figure 7 the following conclusions are worth to be noted: The measurement results verify the characteristic values derived from the theoretical discussion (chapter 2). The values close to the minimum change only slightly while the update time is increased. It follows that the response time average value does not increase at a rate similar to update time. The least beneficial impact associated with increasing update time is on the jitter. This increases nearly proportionally with the update time.

Table 2 shows no substantial difference in the cases when the roles of provider and consumer get alternated between the devices. Further, in none of the cases the measured results exceed the extreme values (maximum and minimum) calculated based on theory.

Based on the measured results it can be concluded that in full duplex communication, the configured devices are equally ranked and both of them can assume the role of provider and consumer.

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