Web remote control of mechanical systems: delay problems and experimental measurements of round trip time

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Summary. The aim of this paper is to show that the web remote control of mechanical system is nowadays not only possible but also efficient due to the improvements, in terms of reliability and bandwidth, of the networks. Nevertheless, as the internet network do not guaranty any quality of services, the possible pertubations (variable delays, failure...) have to be taken into account while developping such systems. We also present some experimental results indicating a relative stability of internet connections in terms of round trip time.

1 Introduction

Currently, the control of mechanical systems is mainly local. With the development of new e-technologies, this control will become remote and made over long distance networks. The problem is to design remote control applications taking into account the following objectives:

- The aims of the industries are to increase the Value Added, to reduce the costs and to transform time into value. So the remote control of machines presents a great interest, particularly for the remote maintenance [2].
- The remote control of machines has to be reliable, fast, easy, protected against attacks or intrusions.[27]
- The used communication technology has to be cheap although it has to offer sufficient bandwidth and small delays.

How to find a good compromise to satisfy these various seemingly incompatible points ?

Our work is based on an Internet approach of the remote control of real machines, a choice of cheap client/server solutions with common operating systems and free software. We want to evaluate the ability of Internet, which is known not to provide reliability, to allow the remote control of mechanical systems in nearly real-time for applications like e-learning, e-practice work, telemaintenance and further e-manufacturing. It corresponds well to the target of the European program "Information Society Technologies" [11], which is to offer "anywhere anytime natural access to Information Society Technologies services for all", and at one fundamental rule of the "Sustainable development" that is to "Rather prefer data transmission than displacement of people or/and matter".

In this paper we propose a cheap methodology to solve the problem of the lack of reliability of the network. Then we focus on the description of our experiments and on results of round trip time (RTT) measurements.

2 Teleoperation and WEB remote control

The main concerns of such a control will be introduced through a historical point of view. The wireless remote control at long distance had been the principal theme of the work of the French physicist and doctor Edouard Branly from 1890 to 1905. The French author Jules Verne [31] wrote in 1875 a speech "une ville idéale, Amiens en l'an 2000" (an ideal city, Amiens in the year 2000) about the city where he lived, and where Edouard Branly was born. One item of this text described the retransmission by remote control in real time of a music concert between concert halls located in Amiens, London, Vienna, Rome and Saint-Petersburg, etc. The work of Samuel F.B. Morse in 1837 on the telegraph was former, but the invention of the telephone by Graham Bell (1874, patented in 1876) was contemporary. Edouard Branly knew the theory of the electromagnetic waves, and the equations of James Clerk Maxwell established between 1860 and 1864. The speed of the light had been calculated by Olaus Roemer in 1675 with a wide error, but measured with accuracy by Hippolyte Fizeau in 1849, as well as the phase speed of electrical waves in conductor wires by Kirchoff in 1857. The propagation velocities of these three kinds of waves are very close and they exceed much those of the material waves in the continuous mediums, e.g. the speed of sound in air measured by Pierre Louis Dulong about 1820, in water measured by Charles Sturm in 1827 and the elastic waves in the rigid bodies. The ratio is near 1,000,000 for the sound and 60,000 for the elastic waves.

The idea germinated of transmit commands to distant systems using electromagnetic or electric waves considering the interest of their high speed. Edouard Branly invented the first electromagnetic waves receiver, the Branly's coherer, opened the way for the invention of the antenna Popov (1897) and the starting of the radio-communication Marconi (1898).

In 1905 Edouard Branly made a successful public presentation of remote control experiments named "télémécanique" (telemechanic) in Paris in the Trocadéro's palace.

The technologies for coding, to transmit and of restitution of information increased considerably during the 20th century. In the second half the computer was born and developed.

The teleoperation became unavoidable during the second world war when started the "Manahattan Project" of production of nuclear weapons. So began in the late fortieth the work about teleoperation performed by Goertz in the Argonne National Laboratory. [6]

The convergence of the information technologies and the communication allowed the birth of Internet and after 1989 the development of the WEB.

During the Nineties, several projects appeared of mechanical systems control using Internet as communication network with varied objectives: the Mercury project

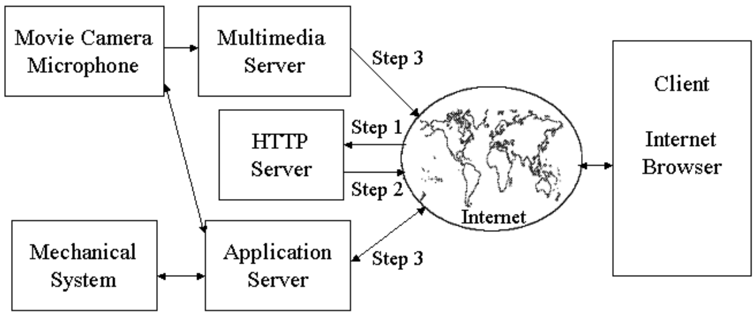

Fig. 1. General Architecture

to prove the feasibility Goldberg and al. [7], the Australian telerobot for the interaction with the user by Taylor and al. [28], Rhino by Burgard and al.[3], Xavier by Simmons [25], Puma-Paint by Stein [26], mobile robotics KhepOnTheWeb by Saucy and al. [23], augmented reality by Otmane Ariti [22], etc.

From the study of these experiments on Internet, a common frame can be described about the operational aspects of an application of e-manufacturing (figure 1). The user, through his Internet navigator, addresses a request to a Web server (step 1) and downloads an application on his work station such as for example a Java applet (step 2). A connection is then established towards the application server in charge of the machines's and client's management (step 3). After checks, the user is able to take the remote control of the remote device. In parallel to step 3, other connections are also established towards multi-media servers broadcasting signals (video, sound) of the system to be controlled.

Even if the general scheme is the same in most applications, no study proposes to develop a generic software architecture. More the unforeseeable nature of network (Internet) was not really taken into account with all its consequences.

In the following part we will propose a solution to these problems and we will present then various applications.

3 Methodology

We have analysed the problem with a discrete events methodology, applied to the run and stop procedures, and we have used a description tool, common in the French industry, the GEMMA [1]. It may be seen as a generic Statechart [10], an empty chart is presented on the figure 9 on appendix.

To take into account the unreliable behaviour of the network, it was necessary to improve the GEMMA . A new form : the GEMMA-Q (Quality of service GEMMA, [20]) have been introduce. 6 levels of quality of communication Q1-Q5 and Qz based on the RTT values have been defined. The state of the system is determined on the level of quality and the server can switch from, for example, the normal production state to a stop procedure when the quality is decreasing, in respect of the transitions specified in the GEMMA-Q, see figure 2.

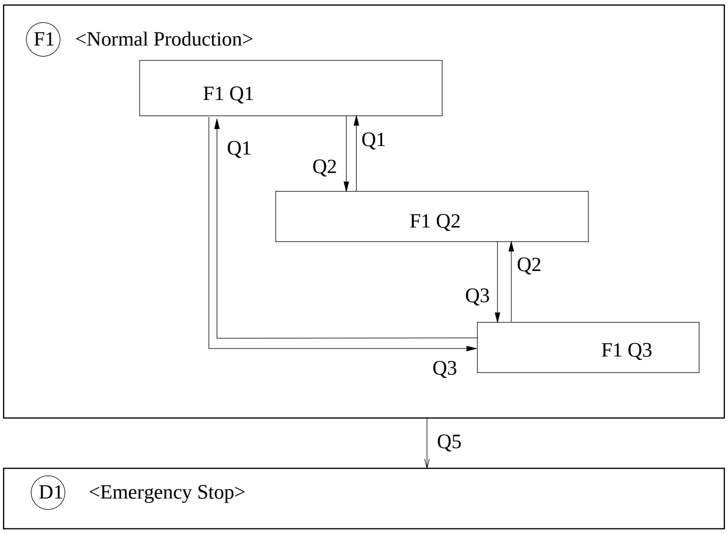

Fig. 2. Substate of the GEMMA F1 and D1

The Gemma-Q is a tool to help the developper while building his application. It forces him to think of the possible problems that may occurs due to network lack of quality of services and to propose solutions depending on the pre-defined quality levels. For example, in the case of a robotic arm, the speed of the movement may be decreased or increased according to the RTT to ensure a proper remote control in any case. More, in case of network failure (connection close), stopping the system is not all the time the best solution. The Gemma-Q offers some specific states (bottom left rectangle on figure 9) to manage defect modes and to describe the procedure to apply in such a case.

States A1 to A7, F1 to F6 and D1 to D3 are the classical states of the Gemma Model. They are all describing some specific activities that may be encounter in production systems like initialisation (A1), production (F2), test (F4 to F6) or emergency (D1). In our proposal, all these states are splitted in substates taking into account the quality of the network. A system can then be on a production mode (F1) with a good (Q1) or a rather good (Q2) or a medium (Q3) quality of the network. Quality Q4 (bad) and Q5 (no connection) forces the system to move automatically to defect mode (D1 to D3).

Developpers will first specify their Gemma-Q while giving an informal description of each state and substates. Then, these states will be instantiated with programs and the whole system is implemented on the machine side. Transitions between states will depend either on external condition (sensors) or on network conditions (quality level). Transition between sub-states only depends on network conditions. The remote user is permanently informed of the situation of the Gemma and of transition between states thanks to our underlying software architecture [21].

This architecture is implemented in java language, and involves few bonds for data- transmissions between the linked threads. This insures a rather good efficiency of the client- server system despite we don't use real time operating systems and true-time clocks. The used operating system for the server is today Windows XP®, but the server runs under Linux as well too. The downloaded code by the client is involved in applets, no plugin is needed. To add new machines we have adopted a plug and play approach, only the driver of the machine on the left side of the figure 3, and the human machine interface on the right side have to be developped. The rest of the system acts as a kernel of transmission services.

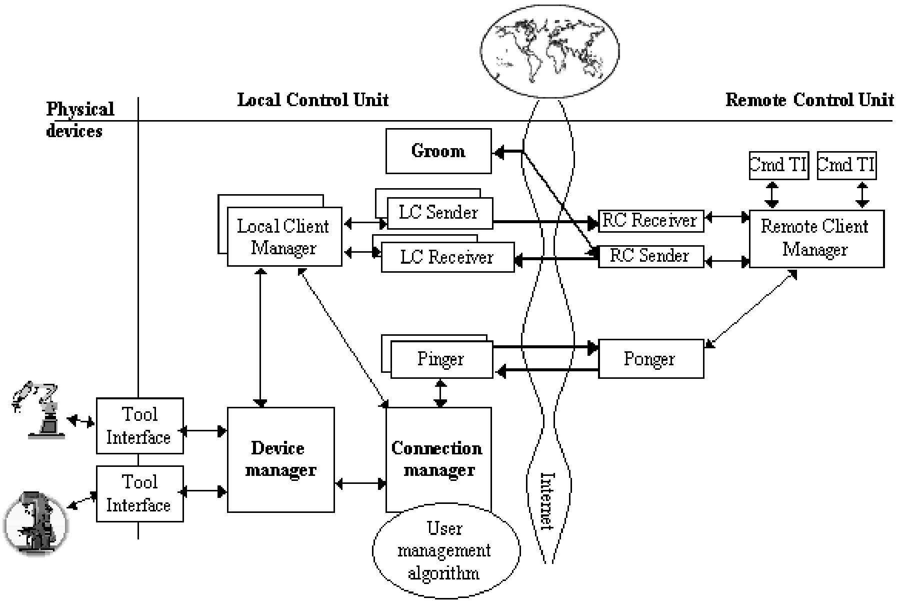

Fig. 3. Architecture of SATURN

4 Applications

Some implementations have been performed:

- a teaching arm manipulator Ericc with 5 degrees of freedom,
- a small milling machine 3d for rapid prototyping,
- a SONY camera (EVI D31) with variable pan tilt and zoom [16],
- a camera with variable pan tilt and zoom in Ocanopolis, an oceanographical museum of Brest, for the observation of penguins [14].

Our system measures every second the Round Trip Time (RTT) between the connected clients and the server software, and stores these measures. The measurement procedure cannot be compared with the ICMP ping command, because this last command is just limited at the border of the operating system at either end, the Ethernet cards, and the net. The ping command sends a frame to the target machine through the net, immediately sent back by the target.

Fig. 4. The robot arm Ericc and the milling machine

Our measures start at the application level on the server, go to the application level inside the client and come back to the server application level. It seems that the periodicities of the tasks of the operating system and the Ethernet cards and their drivers have a strong effect on the collected values e.g. the figure 7, these aren't continuously but discretely distributed. We choose the TCP-IP protocol [19] because, it's behaviour for long distance transmissions is better than with the other protocols : it improves the reliability but it is also considered as less efficient as other ones. So our values are higher than the values collected with a common ping (or a traceroute), but we are able to communicate between protected machines even when the ping command is unusable. More, the exchanged frames contain usable data for the control.

The figure 5 shows our human interface for the remote command of the robot arm. On the right side of the top, the interface displays an indicator of the ping-pong quickness, and draws a bar graph over colored stripes. Each colored stripe matches to a specific level of quality of the communication. The limit values of the levels are based on the reaction time of a worker in front of the machine inside the workshop, e.g. if the distance between the machine and him is close to 1 m, his travel speed in the factory is near 1 m/s, so his reaction time is greater than one second.

In the next section of this article we present our results of measured RTT. They show that today the reaction quickness of a qualified worker far from the machine but well connected to Internet could be better than those of a worker in front of the machine.

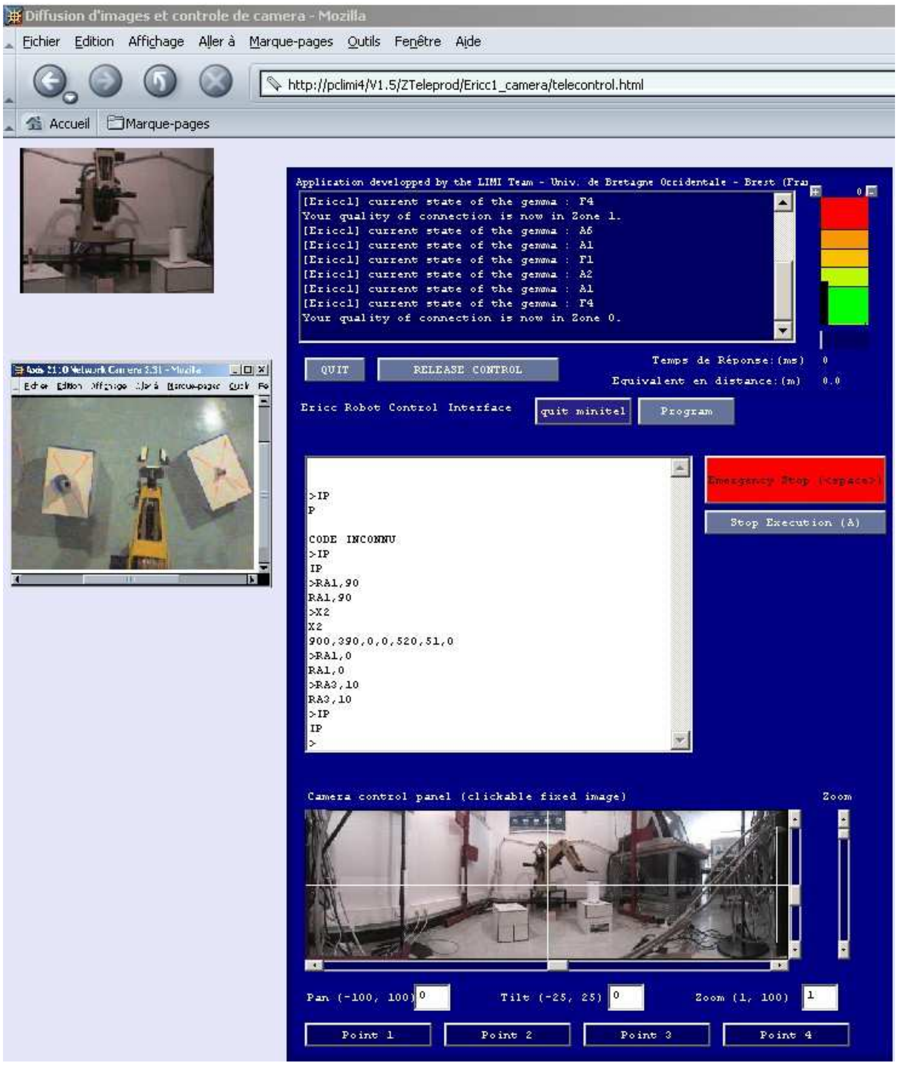

Fig. 5. The client interface

5 Results

Since 2001 we have stored the data of more than 14 000 connections of more than one minute. During the last three years the performances of Internet have been increased dramatically.

We collect the values of each RTT of each connection in html files on our server, so we can access from every where to the data. Each month we transfer all the data on a MySql data base manager and we have written some typical requests to analyse the quality of the connections.

Table 1. Mean measured RTT and durations by kind of connection

	global	from France	from other countries	56k modem from France (Wanadoo)	ADSL from France (Wanadoo)
number of connections	12530	8493	4037	1468	2567
mean duration (s)	240	247	225	214	250
mean RTT (ms)	519	473	602	1023	214
standard deviation (ms)	140	140	35	669	29

The first table shows the collected values between 2001 and 2003, the two last columns display the values corresponding to the french Internet provider Wanadoo. The observed RTT values depend strongly on the kind of the connection on the side of the remote user, with Modem Lines : RTT = 1023 ms, but with Adsl lines from France to France: RTT = 214 ms, always Average values (world wide): RTT = 537 ms. Only 3% of the measured values of the RTT are over 100% of the average value. Although our RTT cannot be compared with ICMP pings, the results of measures performed during the CAIDA project [4] are similar in terms of RTT time. The figure 6 shows the evolution of the quality since august 2001 to november 2004, the percentage of the connections staying in the limit of the pic value under 100% of the mean value was only 10% at the beginning and reaches 40% at the end. We can expect that before the end of this decade less than 10% of the connection will not achieve this criterium of quality. The two bargraphs show the RTT over 50% of the average, and the RTT over 100%, it appears that the stability of the connections are increasing, today we have less than 3% of the connection with abnormal RTT higher than 100% of the average.

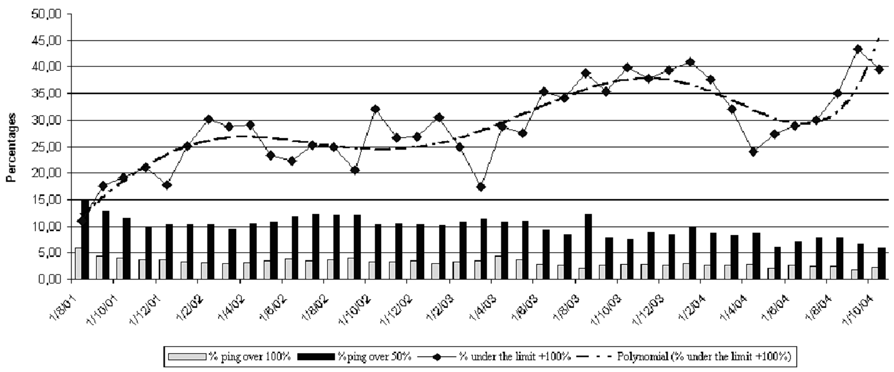

Fig. 6. Evolution of the quality

More, we also have observed a lot of remote connections like the one presented in figure 7 (connection from France to Japan) where the average RTT is equal to

349 ms and all the value are comprised between 270 ms and 490 ms. This connection has a duration of more than 20 minutes.

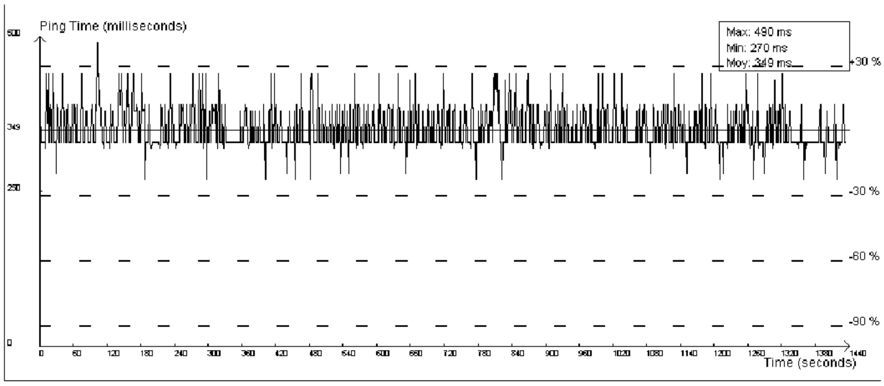

Fig. 7. Trace of a connection between Brest and a remote user situated in Japan

All the previous results seems to show the relative stability of the Internet network. According to us, this stability is the consequence of two main factors :

- We are using the TCP/IP protocol which has been defined to limit, as much as possible, congestion. This protocol uses different strategies, like slow start, fast retransmit or fast recovery, to try to insure a constant rate of the trafic between partners.
- Networks are now a key point of the new economy and the operators have a lot of pressure from their customers to offer the best service. The infrastructure of backbones is generally oversized to be able to manage even the worst case.

This property of relative stability can be used in the context of remote control, first of all to inform the user about the quality of the connection between him and the system he is controlling. It makes it possible to have some prospective idea of what he could do with the system. More, if several users can gained the control of the system, the one who has the best quality should be the one who will get the control.

The second aspect shown by these results is the fact that the average RTT is very small. It opens new perspectives to the remote control, to switch from nice demonstrations of feasebility to real use in the industry.

Nevertheless, these results also show that from time to time, depending on web factors[1](users, providers, operators, international news...), this nice stability and slow delays hypothesis are no longer true. As, the controlled system are mechanical, are moving or making movements, we have to assume security constraints. Our discrete approach with the Gemma-Q is then efficient, because the failure of the transmission occurs only accidentally. Indeed a break of the data transmission remains ever possible and for such a remote control we have to take into account that

[1] The problem remains of the forecasts of the performance in terms of delay and bandwidth of the net, some tools about are developed about e.g. "NWS" by the Network Weather Service (NWS) [5, 18].

the data are transmitted to a long distance without intermediate control nor quality of service guaranteed.

6 Conclusion

Our work started few years ago from a scaling concept based on the observation of the quick increasing of the performances of the IP network, and the standardization of the WEB technologies. We have developped a generic architecture and a specific sensor to measure and evaluate statistically the improvement of the net. The results are better than expected, the RTT values are small and the stability satisfactory. It appears that active remote control is feasible today on a world scale [8, 9, 32], with a rather good reliability and that the whole Internet- world is today within less than one half second for the users having "high speed connections". The physical limit of the speed is the light velocity, we are today between 5 or 10 times lower. If it should be possible to reach the limit in the future, New Zealand will be only at 200 ms RTT of Europe, such a small delay would permit an effective teleoperation [13, 30] with force feed-back on the whole earth! This perspective open the door of networked closed-loop system, where the stabilization problem of the variable time-delay would be solved. [17]

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Appendix

In 2003 we have computed averages for some countries with values extracted from our measurements. It appears that the geographical distance as no significant influence on the RTT, and that the performances are near the interessant RTT value of 300 ms considered as a threshold compatible with the IP telephony.

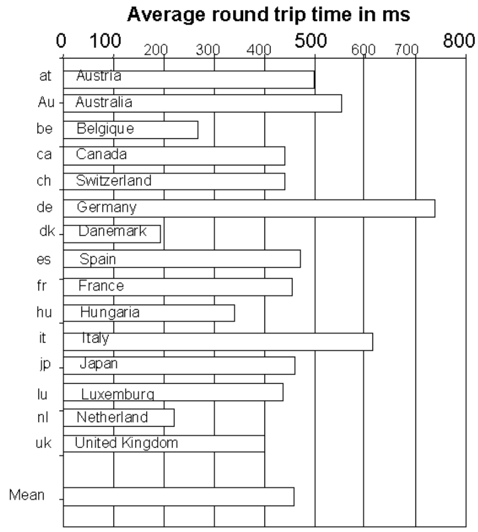

Fig. 8. Measured RTT : mean value versus the country

To evaluate the velocity of Internet today we have tested with some ICMP pings the connection from Brest (France) $48°23'$ N $\oplus$ $4°30'$ W to Auckland (New-Zealand) $37°00'$ S $\oplus$ $174°47'$ E., one of the antipodes city. Each RTT packet covers a bigger distance than 39,000 km. We have reported in the appendix two tables of typical measures of RTT and traceroute, the RTT is not stable, but the values are mostly under 400 ms.

The great-circle distance between these two towns is about 19,500 km. Each RTT packet travels more than 39,000 km. We have reported here two tables of typical measures of RTT and traceroute, clearly the RTT is not stable, the max value is approximately four times greater than the average value, but the values are mostly under 400 ms. So the operational velocity of the data is close to 100,000 km/s the half of the light speed in optic fibers !

This means that the delays induced by the equipments like switches or routers are become very small for the long distance communications on Internet.

Table 2. Sample of ICMP RTT between Brest(fr) and Auckland(nz) and traceroute

```
lepouldu[4] ping -s www.auckland.ac.nz
PING www.auckland.ac.nz: 56 data bytes
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=0. time=390. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=1. time=2154. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=2. time=1154. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=3. time=389. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=4. time=387. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=5. time=443. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=6. time=391. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=7. time=391. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=8. time=389. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=9. time=386. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=10. time=392. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=11. time=388. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=12. time=387. ms
64 bytes from www.auckland.ac.nz (130.216.191.67): icmp_seq=13. time=393. ms
^ C
—-www.auckland.ac.nz PING Statistics—-
14 packets transmitted, 14 packets received, 0% packet loss
round-trip (ms) min/avg/max = 386/573/2154
lepouldu[5]
```

```
lepouldu[6] traceroute www.auckland.ac.nz
traceroute to www.auckland.ac.nz (130.216.191.67), 30 hops max, 40 byte packets
 1 193.52.16.16 (193.52.16.16) 0.721 ms 0.420 ms 0.291 ms
 2 172.31.1.19 (172.31.1.19) 0.593 ms 1.987 ms 1.382 ms
 3 193.50.69.249 (193.50.69.249) 2.310 ms 2.565 ms 2.131 ms
 4 193.48.78.197 (193.48.78.197) 134.774 ms 110.455 ms 111.106 ms
 5 PAO-Rennes2-TR.rrb.ft.net (195.101.145.25) 116.580 ms 115.974 ms 57.848 ms
 6 peering-GIP.rrb.ft.net (195.101.145.6) 19.283 ms 18.024 ms 115.293 ms
 7 rennes-g3-1-10.cssi.renater.fr (193.51.181.126) 37.090 ms 52.776 ms 78.339 ms
 8 caen-pos1-0.cssi.renater.fr (193.51.180.17) 128.701 ms 21.718 ms 20.487 ms
 9 rouen-pos1-0.cssi.renater.fr (193.51.180.22) 39.375 ms 28.154 ms 22.034 ms
10 nri-a-pos6-0.cssi.renater.fr (193.51.179.21) 20.082 ms 32.574 ms 29.953 ms
11 193.51.185.1 (193.51.185.1) 32.696 ms 24.649 ms 23.975 ms
12 P11-0.PASCR1.Pastourelle.opentransit.net (193.251.241.97) 30.294 ms 24.603 ms 19.522 ms
13 P2-0.AUVCR2.Aubervilliers.opentransit.net (193.251.128.117) 21.410 ms 22.717 ms 27.937 ms
14 P6-0.NYKCR2.New-york.opentransit.net (193.251.243.234) 94.401 ms 107.672 ms 113.035 ms
15 P4-0.SJOCR1.San-jose.opentransit.net (193.251.242.2) 180.001 ms 175.272 ms 175.997 ms
16 P8-0.PALCR1.Palo-alto.opentransit.net (193.251.243.121) 176.130 ms 175.997 ms 175.436 ms
17 134.159.62.5 (134.159.62.5) 175.075 ms 177.357 ms 176.800 ms
18 i-11-0.paix-core01.net.reach.com (202.84.251.21) 182.981 ms 180.188 ms 177.993 ms
19 i-13-0.wil-core01.net.reach.com (202.84.143.61) 186.890 ms 187.118 ms 186.342 ms
20 202.84.219.102 (202.84.219.102) 662.074 ms 517.804 ms 675.547 ms
21 ge0-2-0-2.xcore1.sym.telstraclear.net (203.98.4.2) 402.907 ms 389.516 ms 389.461 ms
22 ge-0-2-0-21.jcore2.acld.clix.net.nz (203.98.50.8) 397.587 ms 388.412 ms 389.480 ms
23 218.101.61.11 (218.101.61.11) 543.061 ms 455.813 ms 496.482 ms
24 clix-uofauckland-nz-1.cpe.clix.net.nz (203.167.226.42) 388.648 ms 391.259 ms 399.452 ms
25 * * *
26 * * *
27 * * *
28 ^ C lepouldu[7]
```

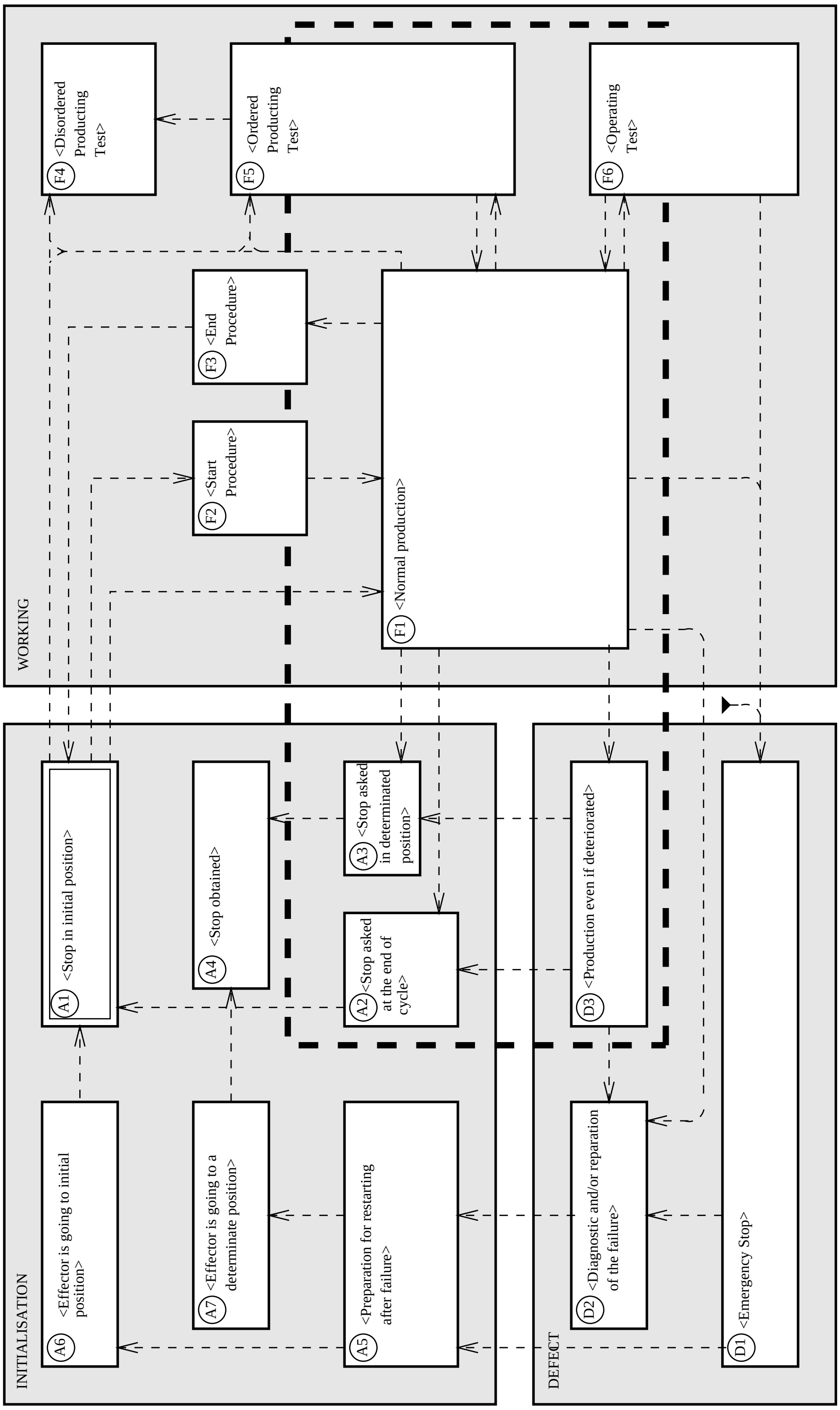

Fig. 9. Classical GEMMA

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