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TERMAN PROJECT, A NEW TYPE OF MASTER SLAVE MANIPULATOR

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ABSTRACT:

TERMAN-TAO is a new type of heavy duty long range manipulator. Its main feature is that the slave movements are operated through a set of electrical motors, while the orders are given by the operator through the use of an electrical master arm. The system provides full range high performance force feedback to the operator. Main objectives of the system are:

- Decrease of the dose exposition of the operator
- Decrease of the operator's fatigue, thus enabling longer and high quality working period
- Robotic mode
- MTBF increase
- Space operating field increase
- Better ergonomomy in working station.

The system has been successfully tested at prototype stage, and is now under full industrial development.

CONTENTS

1. Introduction
2. TAO concept : principles, gains
3. Terman concept : description, gains, applications
4. Results of the initial validation phase

GRATITUDE

With warmest thanks to AREVA and CEA-LIST for their kind support and valuable contribution.

1. Introduction

1.1 GETINGE LA CALHENE

Getinge-La Calhène has been involved in designing ever safer tools for the protection of workers and for safe handling of unstable materials in the nuclear industry since the 1960's. Specializing in manipulators, sealed transfer systems and transport packages, Getinge-La Calhène provides equipment to protect the client's product from the environment, and protect the customer's personnel and facilities from potentially dangerous products.

The expertise acquired in the nuclear and nuclear medicines markets has been applied to the healthcare sector. Sealed transfer, transport systems and isolator units are supplied to hospitals, clinics, sterile production and pharmaceutical facilities in order to protect patients and health workers as well as to maintain sterility

1.2 Telesmanipulation and robotic history, background

For almost 20 years, the CEA LIST and AREVA have carried out a collaborative program of ambitious developments to improve interventions in hostile environments. These developments have led to the realization of high performance telerobotic systems based on proven and reliable industrial technologies. For AREVA, a continuous and sustained improvement program has been in place since 1998. It started with an industrial robot in a hot-cell for the repair of an iron-boiler made equipment. This robot then ensured the maintenance of large strategic pieces of equipment in the so-called "mechanical cells".

Most of the development was performed in La Hague factory where in particular a "TAO 2000 software platform" was installed. The concept of a wall installed Master Slave Manipulator using TAO technology was born in La Hague, since this huge nuclear place uses around 500 MT200 MSM continuously, and in tough conditions for a significant part of them.

1.2.1. GETINGE LA CALHENE MT200 mechanical system (original system)

In order to operate nuclear installations with large hot cells, GETINGE La Calhène developed a mechanical master slave system with a telescopic arm with the CEA in the 1980s. The working volume of this type of arm can go up to 4,5 meters. Using these systems, it is possible to run and maintain the large hot cells in excellent conditions. These remote manipulator arms are often used alongside lifting cranes to move heavy loads (above 10 kg).



MT200 - GETINGE La Calhène

The MT200 system is composed of a slave arm in the hot cell, a wall through tube and a master arm in the cold working area. The MT200 system components can be disconnected in three independent parts. The master arm is compatible with several slave arms. The wall through tube model depends on the thickness of the wall.

Depending on the radiological environment, the slave arms may be equipped with a protection sealing sleeve or a semi sealed sleeve or a double sealing sleeve. The protection sleeve implies that the slave arm may be changed through the cold operating cell area. This protection system and operations leads to a better protection of the arm, and therefore an improved MTTR (Mean Time To Recovery). It also significantly lowers the cost of waste treatment and decontamination operations.

1.2.2 The new generation

Using the existing MT200 equipment, AREVA has developed the new concept of:

- first the MT200-TAO, where the mechanical master slave is replaced by an electrical master slave arm through a computer and an electrical power block engine.
- secondly, the TERMAN-TAO, where as compared to the MT200-TAO, the slave arm is replaced by the TERMAN arm.

These two concepts extensively use the TAO technology developed by CEA LIST.

The TERMAN slave arm technology is developed by GETINGE LA CALHENE, who is also the industrial leader of the industrialization of the two said new generation systems, MT200 TAO and TERMAN TAO.

GETINGE LA CALHENE's main subcontractor CYBERNETIX is in charge of the supply of the main controller, software and interface controller based on their CYXPRO technology.

2. The TAO Concept

The TAO or "Telemanipulation Assistée par Ordinateur" (in English : Computer Assisted Telemanipulation) is very comparable to the "fly by wire" technology now in use in most aircraft. It consists mainly of:

- breaking the mechanical link between the operator and the top end of the slave arm,
- replacing human energy by electricity: the movements of the slave arm are powered by motors,
- integration of a fast computer in the loop, which analyzes the operator orders and transforms them into orders to the motors.

The TAO concept, and specific software, have been developed by the CEA. They are used in a number of applications, thanks to a universal and modular approach.

The following breakthrough are of note :

- the system provides exceptional feed back to the operator (no delay, 7 axes),
- the ratio of efforts between slave and master arm is adaptable : we decided on a ratio of 10 in our applications (1 kg at handle gives 10 kg at tong),
- the software allows for some smart application such as filtering of vibrations as an example,
- the software protects mechanical and electrical parts against overpassing the demonstrated performances, thus reducing the number of failures.

2.1 Goals and differences between the MT200-TAO system and the standard mechanical MT200

The new system requirements are the following:

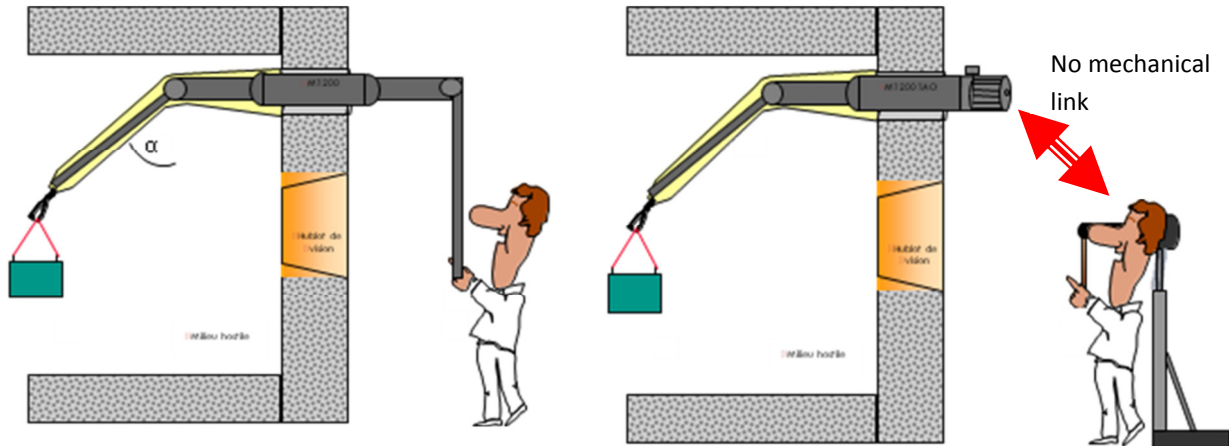
- Higher availability rate
- Lower maintenance cost
- Lower workers dose (with respect to ALARA principles)
- Better performances (load and work area)
- Safer and ergonomic use (Human factor)

The following picture describes the new system concept (patented by AREVA and CEA). The main idea is to get rid of the mechanical link between the master arm and the slave arm. It is

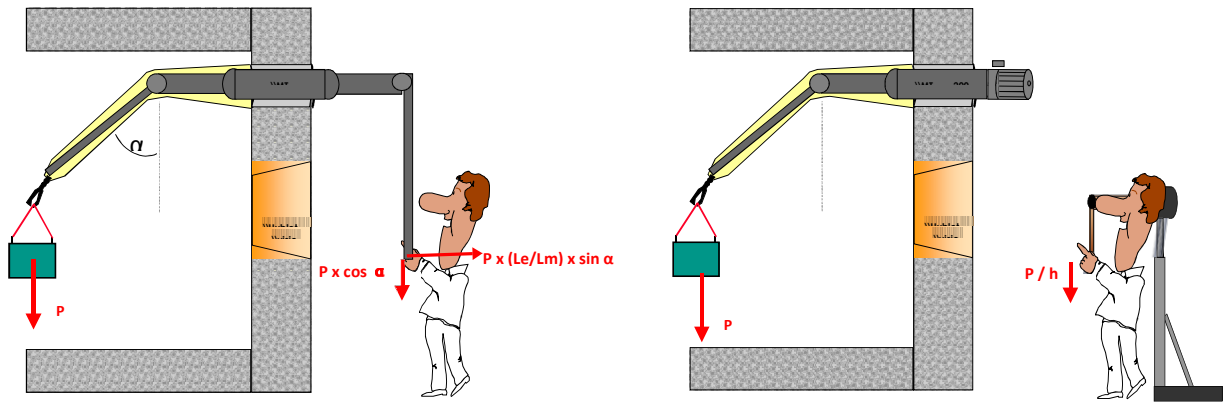
then replaced by an electrical link. This strategy allows the operator to be freed of the constraints due to the system, and reciprocally. Moreover, the mechanical weakpoints disappear, such as arms balance and directional axes connections. They are replaced by software applications.

MT200 mechanical system

MT200-TAO system



The main operating differences between the two systems lie in the master arm sub-system. The large historical master arm has been replaced by a polyarticulated small master arm. The operator still moves the handle in the movement direction, and the slave arm movement follows the same path, with respect to a homothetic ratio. The force feedback (on both master and slave sides) is transparent and does not depend on the slave arm position, as shown on the picture below.



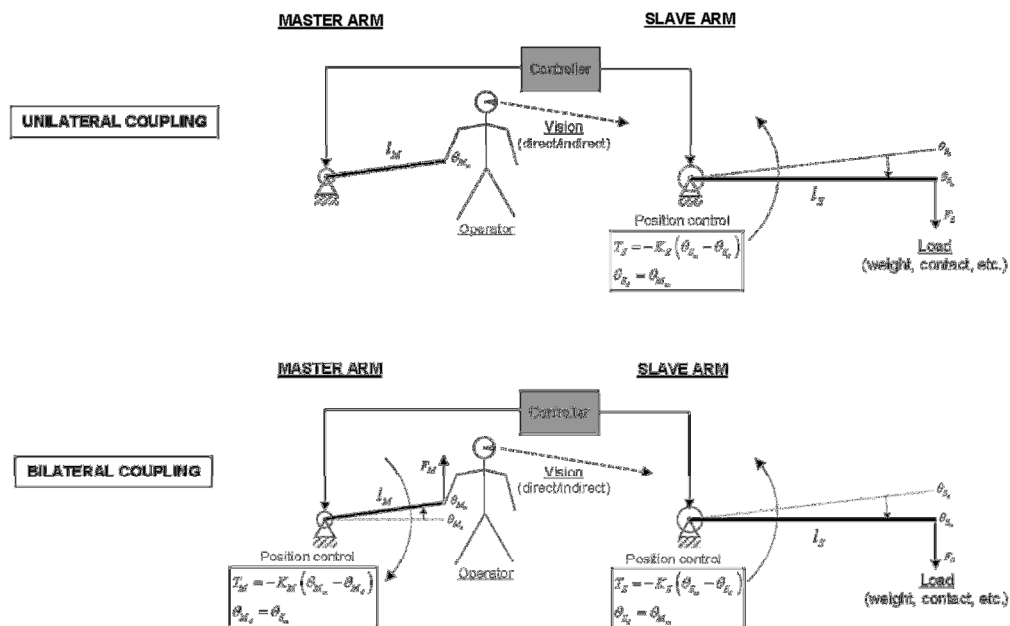
The operator can always be well positioned for the task in hand by shifting the master arm with a push button. In order to simplify the operations, internal movements e.g. the electrical telescopic motion are automatically driven. The operator can be positioned anywhere (direct vision, camera vision, control room operations) thanks to the electrical link between the master and slave arm. This major benefit is not affected by operational constraints, such as correlation between hand motion and visualisation of this motion thanks to the operating software. The latter calculates the slave arm position with respect to a reference point and the master arm position. Finally, software operational assistance is available, such as partial or total load compensation, claw safety, claw rotation, or virtual axes lock on.

Additionally TAO provides:

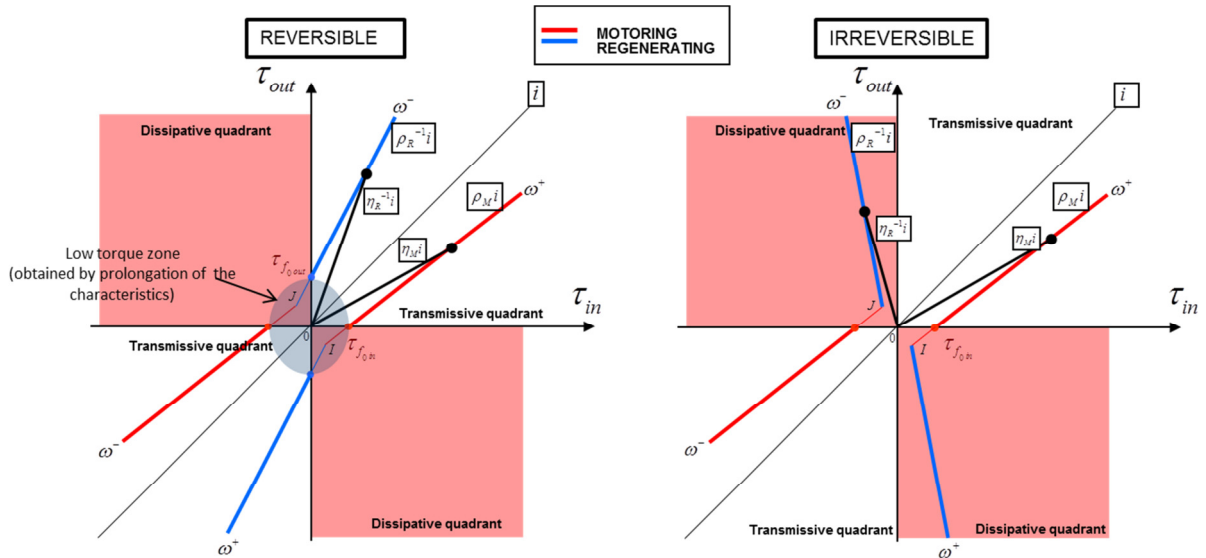
- full load compensation: means that the operator never feels the weights and inertia of the system,
- automatic mode (robotic mode), and shared modes (manual + automatic),
- disconnection between the operator and the operating area, for more flexibility and higher safety (ALARA principle).

The TAO concept is the result of research and development that were performed by the CEA-LIST, in particular in the areas of:

- mechanical reversibility



- quality and characterization of the transmission



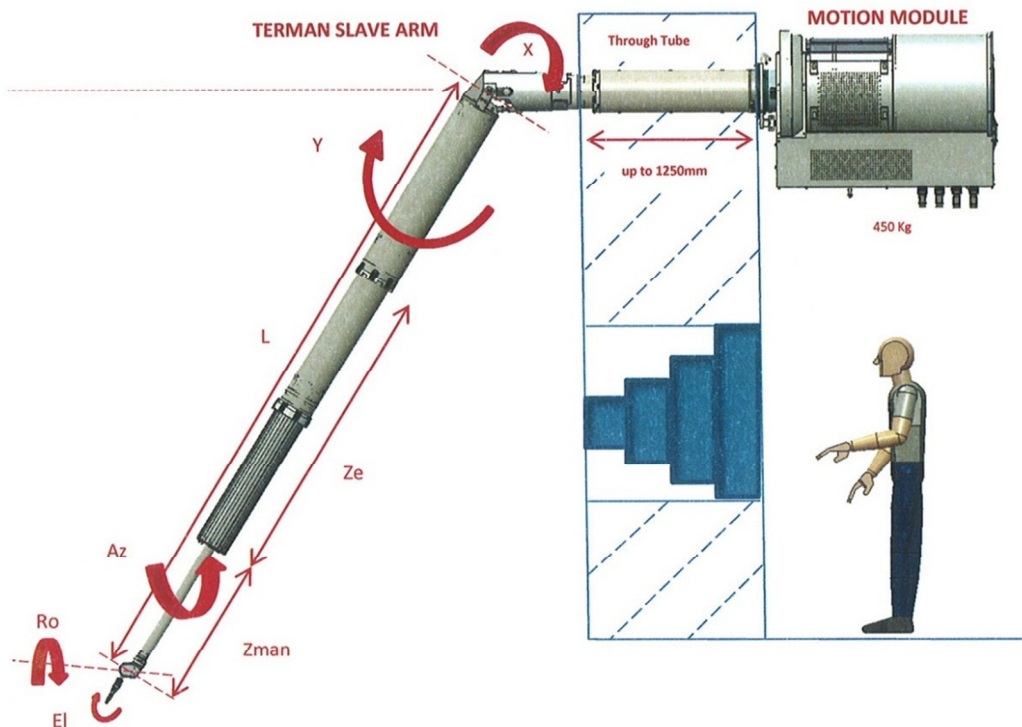
3. Terman concept

3.1 Description of the slave arm

The TERMAN slave arm, a mechanical arm with 8 degrees of freedom, is used for manipulation inside confined zones, also known as hot cells or active cells, in the nuclear industry. The connection between the master arm and the slave arm is electrical instead of mechanical, thereby eliminating friction in the entire system and enhancing force feedback.

New generation kinematics are achieved by drive shafts and gears. Robotic mode is enabled by the absence of cables (unlike preceding generations of manipulators e.g. MT200) which greatly improves precision and rigidity.

The kinematics can be stopped or started at the through tube by sets of motion couplings; The motor module or the slave arm can also be disconnected from the through tube by the same straightforward, quick method.



3.2 Gains

The TERMAN TAO provides the user with gains at several levels : operational, technical, radio-protection (dosimetry) and economical.

3.2.1 Operational

The TERMAN TAO manipulator provides the operator with a permanent ideal working position and vibration filtering plus full range high performance force feedback, thereby reducing effort and fatigue while improving accuracy and efficiency.

3.2.2 Technical

The operating field is significantly increased since the slave arm covers an area 3 times that covered by the MT200 TAO arm, on which the design is based.

Robotic mode provides optimal precision and speed for repetitive tasks.

3.2.3 Radio-protection (dosimetry)

Thanks to the significant distance between the operator's work location and the hot cell, together with the reduction in working time due to the increase in efficiency, the operator's dose exposure decreases.

3.2.4 Economical

Benefits for the operator give improved accuracy and efficiency, with cost savings in the long run. The state-of-the-art equipment is more reliable, limits to effort having been programmed at the TAO level, thereby increasing MTBF and bringing maintenance costs down.

3.3 Applications

The TERMAN slave arm is capable of manipulating a wide range of objects with a high level of precision, from the very light (e.g. changing a light bulb using manual mode with tongs) to the very heavy (capacity up to 80 kg on hook). The operator can define highly specific working ranges, i.e. between 0 kg and 0.5 kg and gets very sensitive feedback from the tongs. TAO (feedback) mode gives the user ease of operation with heavy load. A 20 kg load is perceived in user feedback as 1 kg. Tools for grinding, shearing and chiseling are available.

Its 4 telescopic tubes give the TERMAN slave arm a working range of between 1460 cm and 4010 cm. The arm can lift 20 kg in all positions with minimal flexure, 40 kg in the vertical axis and 80 kg on the hook. The cable-less arm contains gears and bars so is entirely rigid.

In robotic mode, operations are done in virtual reality then applied in real time. This limits friction and promotes efficiency since recurring manipulations are repeatedly carried out with the same precision. Robotic mode is particularly useful for screwing and unscrewing items inside the hot cell.

4. Initial phase of concept proof

Before launching the full industrialization phase two main validation phases were performed both at system level (MT200 TAO mainly), and for the TERMAN slave arm concept itself.

4.1 System level

This proof of concept phase was performed by AREVA using the prototype of the MT200 TAO, in situ. The purpose of the implementation of the system MT200 TAO was to validate the performances of the new system and also to verify that this type of tool could be used daily by b operators without specific qualification and to analyze the effects on their working conditions.

4.1.1 MT200 TAO operational testing methodology

Cold cell system testing:

As for any industrial system, AREVA has put together a complete benchmarking and testing process in a cold testing hall at La Hague plant. During the tests, operational performance was checked, as were small modifications made in order to meet requirements. A group of operators was then trained.

Hot cell system testing:

The choice of the place and type of operations for the system prototype was made in order to maximise the amount of lessons learned on the new system with the following criteria :

- Continuous use, in order to maximise the amount of information and test MTBF.
- Used in representative La Hague operational positions.
- Demanding solicitations of the system, with a real operation gain on the tasks.
- Testing a working volume three times larger than the standard operating volume.

Operations put on the agenda for this testing phase were:

- Cleaning of vitrification crucible using an automated chipping tool.
- Alpha glass and frame cleaning. This operation needs dexterity and flexibility.
- Handling, cleaning and tidying of the cell.
- Light and lifting maintenance.

4.1.2 Results of operations during the testing campaign

Operational benefits:

It was demonstrated that the MT200-TAO system brings a 60 to 65% productivity gain. This is due to the fact that the system is easier and lighter to use, and the operators can therefore work more quickly over longer periods of time. Using the MT200-TAO system, an operator may be effectively working during 6 hours.

Additionally, the motions are more precise using the MT200-TAO system. It was shown that this precision brings a productivity gain of 20%.

Maintenance benefits:

During the 10 months operating the MT200-TAO system, operators had to change one slave arm and 4 knee levers. With respect to lessons learned with a standard system, that maintenance means a saving of 5 slave arms. This implies that there is a gain in the cost of these arms and time used to work instead of maintain, but also due to the fact that no additional waste had to be sent to the waste center, and that the hot cell was available for its functions during additional time. There was no maintenance of any kind necessary on the operator side for the system. The entire system performed as intended.

Human factor benefits:

The operators working on the hot cell had undergone training for their work in a similar cold (standard) environment during a few days. Therefore, tests were organized in this cold training cell, in order to measure and evaluate the changes brought by the system in terms of ergonomics, ease of work, and stress (duration and intensity) transmitted to the operator. They were defined so as to evaluate different types of tasks, which required precision or manipulation of heavy loads.

A data sheet with operators' impressions was put together and filled by every user in order to build feedback on their impressions.

a) Physical strain reduction

- Physical stress on the operators is considered as « light », compared with that caused by the standard mechanical MT200, classed as « heavy».
- Fatigue is felt less by the operators, especially on the shoulders, back, hands and arms.
- Force feedback is lighter when using the MT200-TAO system than when using the MT200 system.
- The “weight compensation” system in the TAO software leads to an easier carriage and movement of the weight.

The MT200-TAO frees the operators from the constraint of being positioned in accordance to the master arm position on the wall. Therefore; there is a significant gain for the operator with regard to his direct or indirect vision. The system allows the operator to be standing facing the window or camera screen, even though the slave arm may be operating significantly aside. Therefore, the body posture is better, and the movements more specific.

b) Mental strain reduction

- It has been noted that mental stress was reduced when using the MT200-TAO system by comparison with the standard mechanical MT200.

- When working above the arm reach or with indirect vision, there is less strain on the operator thanks to the MT200-TAO. The system allows a good match between the operator vision and its manipulation. The operator doesn't have to adapt to a "mirror" or upside down motion.

c) Safety features

Since the slave arm is not linked mechanically to the master arm, it is possible to place the new master arm in a safe location. Therefore, the operator is in a less irradiating zone, with no equipment above his head or contamination risks. The work area is made "accident proof" by avoiding interactions with the surroundings.

d) Overall lessons learned.

Feedback from the operations and operators leads us to the general conclusion that the MT200-TAO system brings 90% satisfaction, mostly due to easier working conditions and less physical and mental strain.

Moreover, the TAO system allows new developments that reinforce safety, health and working conditions.

The development of this new system included from the beginning all the constraints and difficulties met during operations (operator's postures, vision limitations, heavy weight lifting, and mirror motion).

This type of system should allow new operators to enter the manipulator business, especially women, with less need to be physically resilient.

4.1.3 Main conclusions

The operators can learn quickly to use the system, and there is a significant gain in efficiency of the teleoperation stand possible with TAO systems.

- The durability and low maintenance of the system were features that led the operators to master the system and use it frequently.
- The decrease in maintenance frequency proved that the system is reliable. This leads to:
 - Higher system availability rate.
 - Significant decrease in the waste volume.

4.2 Terman slave arm proof of concept

In order to validate the concept of Terman slave arm a technology demonstrator was built by GETINGE LA CALHENE and extensively tested.

The huge experience gained through this demonstrator has proven the Terman slave arm to be the right concept capable of meeting the operational performances requested by AREVA especially.

In particular, the essential criterion of friction thresholds was fully achieved; in the worst case, the measurements were less than half the limits fixed by the specification,

The arm flexion at maximum useful load (20 kg) when horizontal and at full extension is around 10 times less than that of the MT200 arm (1°).

The demonstration also proved that load variation has little influence on the Terman arm performances. The arm's linearity was demonstrated by the dry friction laws at manual Z axis.

The major characteristic of the Terman arm design, i.e. the lack of electrical power components on the slave arm, gives the following advantages :

- resistance to the aggressive nature of the operating environment
- suppression of the risks and complexity linked to electrical interfaces, in particular for the disconnection/reconnection requirements during slave arm replacement and, in addition, the straggler supply and control cable for the motor at the end of the arm.

In addition, we are certain of obtaining a precise force feedback which considerably improves the reliability and operating life of the slave arm while greatly increasing ergonomics for users.

Par ailleurs, la rigidité structurale et la faiblesse des jeux mécaniques mis en évidence par la démonstration augurent d'excellentes performances en mode robot.

Moreover, the structural rigidity and low backlash which were demonstrated predict excellent performances in robotic mode.

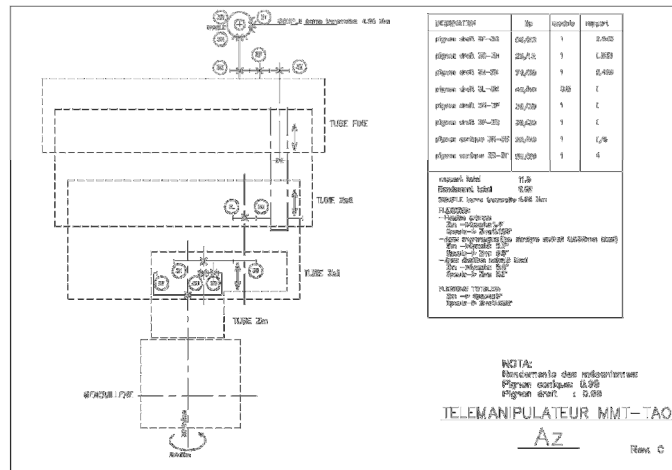
The demonstration phase of the Terman arm design validated 3 important parameters :

- a) the mechanical feasibility of the shoulder

- b) the merits and satisfactory performances of the concentric rods and gears
- c) the amount of mechanical friction

4.2.1 Shoulder Feasibility

The mechanical couplings are realized by conic drive shafts placed on the articulation axis. All the movements must be contained within a space compatible with the future installation. All the movements transferred by the shoulder were measured, all the kinematics described, and the shoulder design was proven to allow passage through the standard 10 inch through tube.

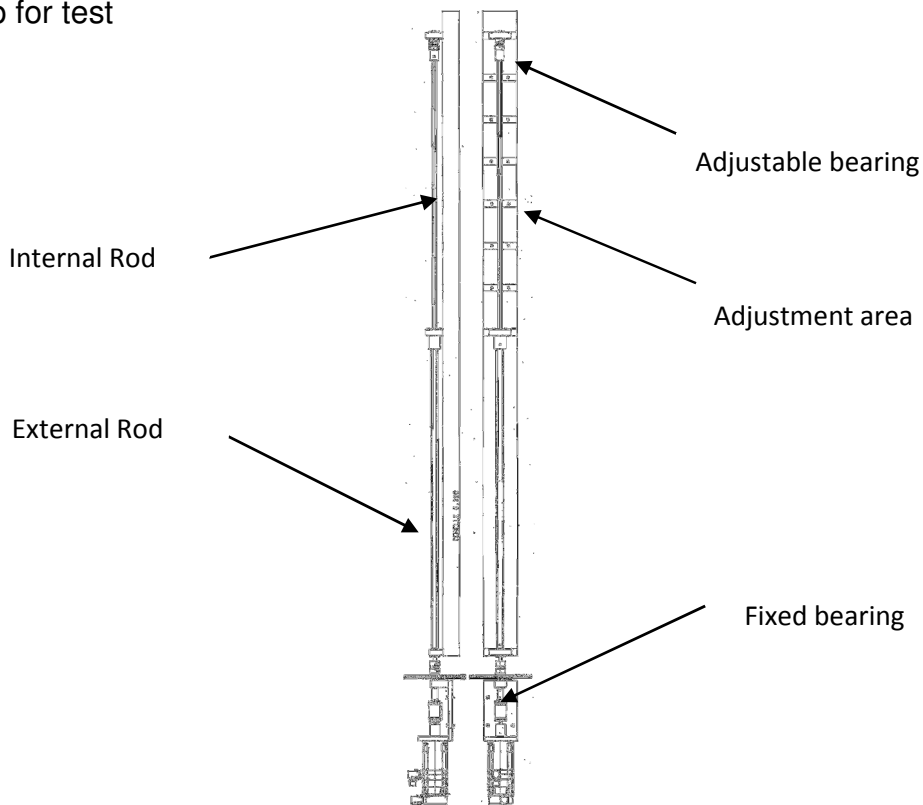


Example of kinematics description (Azimut)

4.2.2. Conic drive shafts

The objective is to prove that the principle of fluted shafts installed in a concentric configuration suits the various movements and rotation speeds of the associated shafts. This configuration is an imperative in the TERMAN project, to limit the size of the slave arm.

Mock up for test



Measurements are taken at 3 speeds for each of the exit positions of the internal shaft. The behavior of the concentric shafts is noted at each position and speed, the latter being 500, 1000 and 1500 TR/min. The concept of concentric shafts functions up to rotation speeds much higher than those required by Terman slave arm.

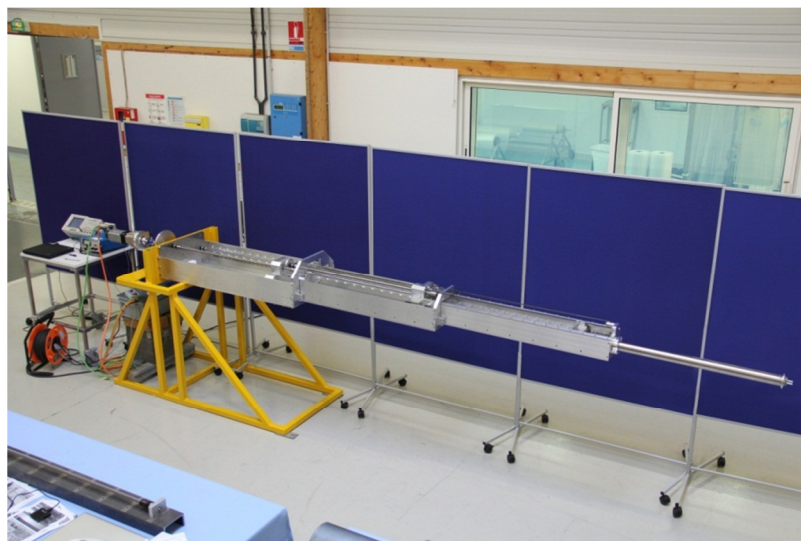
4.2.3. Mechanical friction and rigidity

The arm of this part of the validation phase was to :

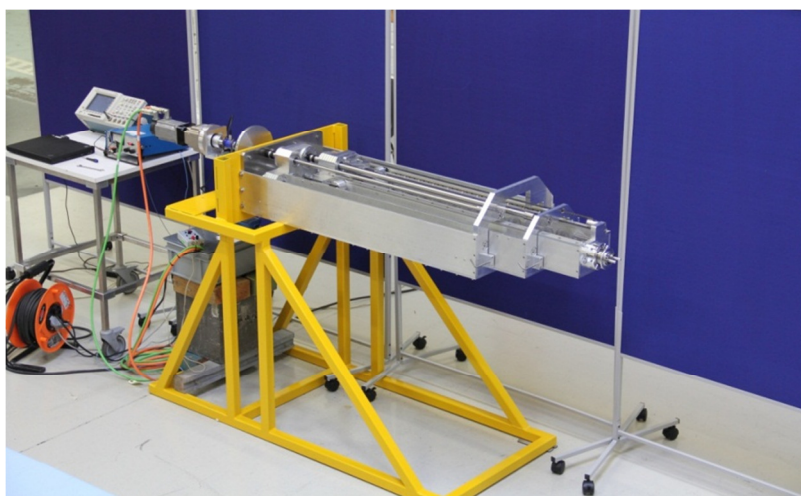
- confirm that the friction levels are below the acceptable limit,
- confirm the rigidity of the structure.

4.2.3.1. Description of the demonstration equipment

The model is built around four telescopic elements, designed to reproduce the Z-axis movement of the slave arm. The first element is fixed while the two following elements correspond to the “Z electrical” movement; the final element represents Z manual movement.



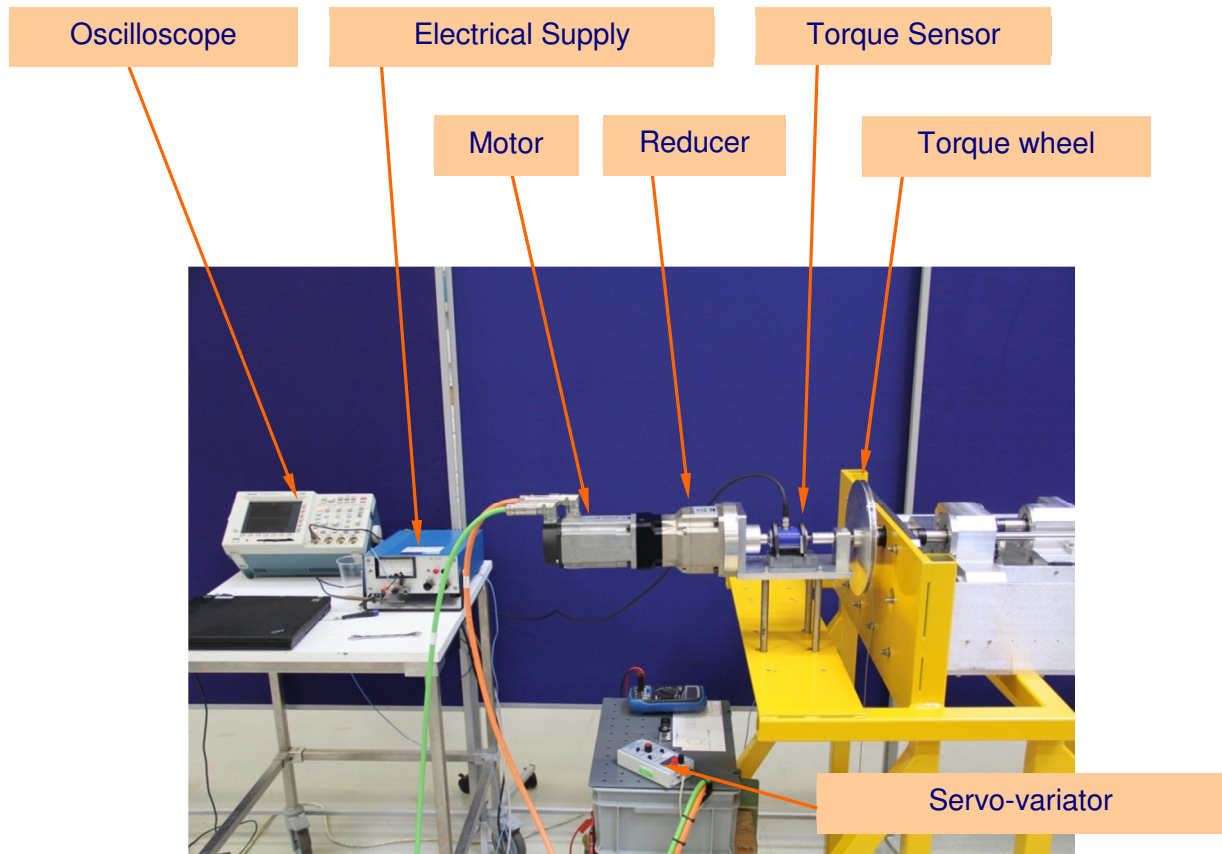
TERMAN MTT model – view with arm in full extension



TERMAN MTT model : view with arm in retracted position

Three movements were realized in this model : Z manual, G1 and G2. The Z movement corresponds to the telescopic extension of the arm while G1 and G2 commandes combined simulate rotation, elevation and clamping of the tongs. The tongs (normally mounted on the arm end when extended) were not integrated into the model.

4.2.3.2. Test material and methods



Matériel utilisé pour la mesure

4.2.3.3.1. Z manual transmission

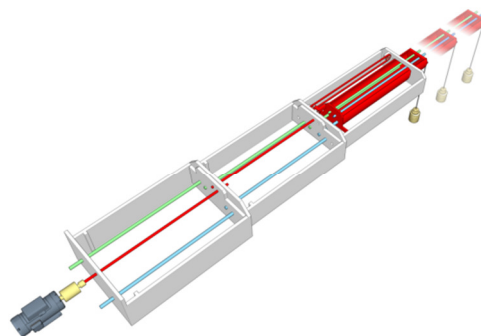
The measurements determined the following :

Influence of internal constraints

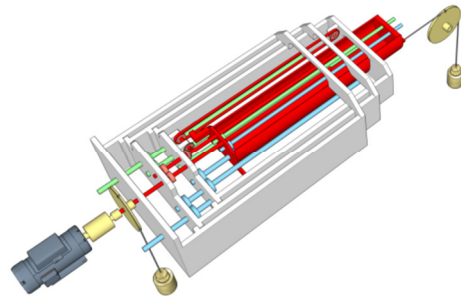
Influence of couplings transmitted on an upstream axis

Influence of flexion moment

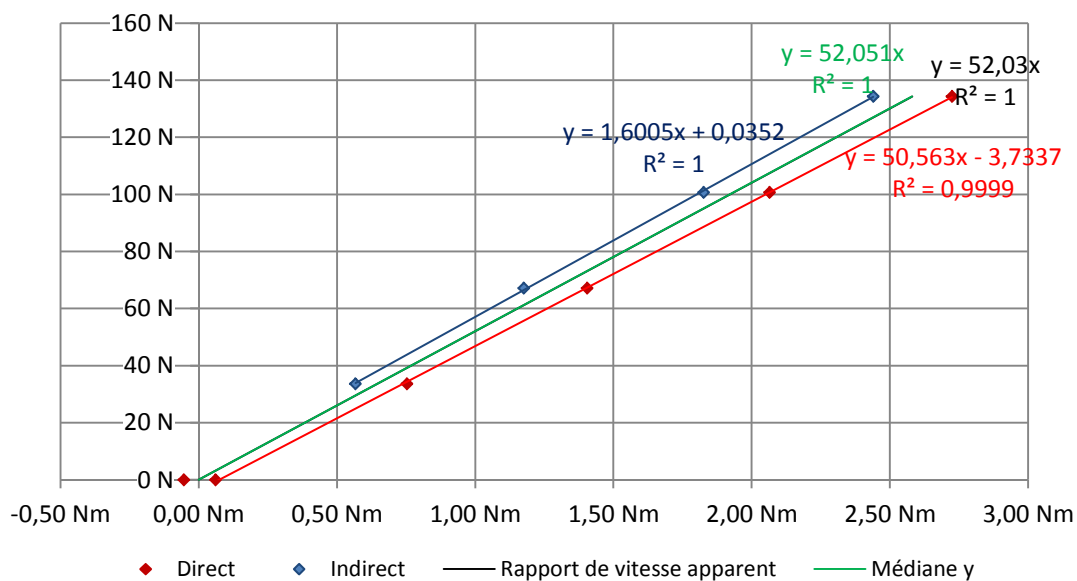
Laws of dry friction



Measurement Configuration for Flexion moment influence



Measurement Configuration for dry friction (manual Z)



Law of Z manual direct and indirect friction

The curves show that the points are well aligned (high correlation coefficient of the straight lines of regression). The thresholds can be calculated :

- ◆ Direct threshold (intersection of red curve with the y axis) = 0.074 N.m.
- ◆ Indirect threshold (intersection of blue curve with the x axis) = 3.4 N.

Le critère de référence obtenu avec le MT 200 TAO étant de 10 %, les valeurs ci-dessus sont excellentes.

Referring these values to the maximum values (in full load) we obtain the following thresholds, respectively

- ◆ Direct threshold = 2.7% (max permissible value = 10%)
- ◆ Indirect threshold = 2.6% (max permissible value = 10%)

4.2.3.4. Conclusion

The tests therefore demonstrate that the proposed solution perfectly meets the constraints of the requested performances, particularly :

- The levels of friction are at all times lower than the reference values previously established on the MT200 TAO prototype phase, both when empty and in the most rigorous conditions of full load and full extension.

- The coupling between the different movements is low, as the friction measurement on one axis(Z manual) showed, when another axis (G1 or G2) was in stress..
- Finally, the performances obtained show that the concept proposed by Getinge-La Calhène satisfies the requirements of Areva's specification.