Weight Reduction: A Typical Issue in the Mechanical Design of Robotic Systems

Nestor Eduardo Nava Rodriguez*

Carlos III University, Calle Universidad, 30, 28911 Leganes (Madrid), Spain

Abstract: This paper illustrates the importance of weight reduction in the mechanical design of robotic systems. Safety and power consumption are the important aspects that deal with the reduction of robot weight for practical applications in the human being environment. A novel approach has been assumed in order to avoid these problems keeping the lightweight of the structure. The weight reduction of the mechanical structure helps to obtain final solutions with feasible characteristics of compactness, robustness and stiffness. These ideas will be explained *via* several examples. The design process of a new arm has been reported from the study of the mechanical details of a built prototype that presents unsuitable weight. Toques of actuating joints have been checked, at the end of the design process, by developing dynamic simulations of robot operations in order to validate the proposed approach.

Keywords: Robotic Systems, Mechanical Designs, Weight Reduction, Mass.

1. INTRODUCTION

Robots that interact with humans are looked for presenting lightweight in order to reduce the impact force magnitude in case of collision with somebody. Similar, the compactness and robustness of robot structure is required, thus actuation system should be compact and robust too. Therefore, lightweight structures allow the selections of low dimension actuators since low actuating torques are required. Moreover, several robotic systems, such as humanoid, quadruped and hexapod robots, try to copy the nature in several ways. Proper weight is required to be fulfilled in order to obtain a robot as nature as possible.

Humanoid robots represent the most complex systems in the robotic field, whose design and construction are a challenge for researchers in several fields of science and engineering. In the last decades, several researchers have investigated achieving human-like behavior and design. Humanoid platforms have been developed with different solutions, as shown in Figure **1**. Most of the available humanoid prototypes have a high number of degrees of freedom, complex control and high weight as well as cost. One alternative of these solutions is to design novel humanoid robots that can be built with commercial components and that can be easily programmed, as reported in [4].

Figure **2** shows an alternative design for a humanoid robot with simpler mechanical structure and operation. The proposed machine is composed of reduced number of actuating joints, articulated mechanisms, and commercial components. The robot control is based on low-level strategies managed by a commercial PLC. This humanoid has been conceived by applying a novel approach for obtaining lightweight as well as robust solutions and compact designs. In this paper, this novel approach is described using illustrative examples. A proper material selection; mechanical designs with feasible features; synthesis of articulated mechanism for the structure; structural analyses; and a proper design of the robotic joints are main tips that provide mechanical designs with the above-mentioned characteristics.

Moreover, the proposed approach can be also applied to complex machines with high-level performances, as those of Figure **1**. This strategy allows for improving the mechanical aspects of robots that increases their capabilities.

A practical application of the proposed approach is the design of a new mechanical arm for a mobile robot. The new design has been obtained from the weight improvement of a previous arm sub-system. Commercial components, as part of the mechanical, electronic and control systems have been also taken into account for obtaining the final robot weights. Outputs of the actuating joints have been computed, by using dynamic simulations of the robot operation, in order to check that the new arm capabilities are similar to the previous prototype. The new arm structure presents feasible characteristics for a serial manipulator in industrial or non-industrial applications.

2. PRACTICAL APPROACH FOR WEIGHT REDUCTION

Some guidelines must be taking into account in the mechanical design in order to reduce weigh. Now,

---

*Address correspondence to this author at the Carlos III University, Calle Universidad, 30, 28911 Leganes (Madrid), Spain; Tel: 0034916898094; Fax: + 34916249430; E-mail: nnava@arquimea.com

E-ISSN: 2409-9694/14

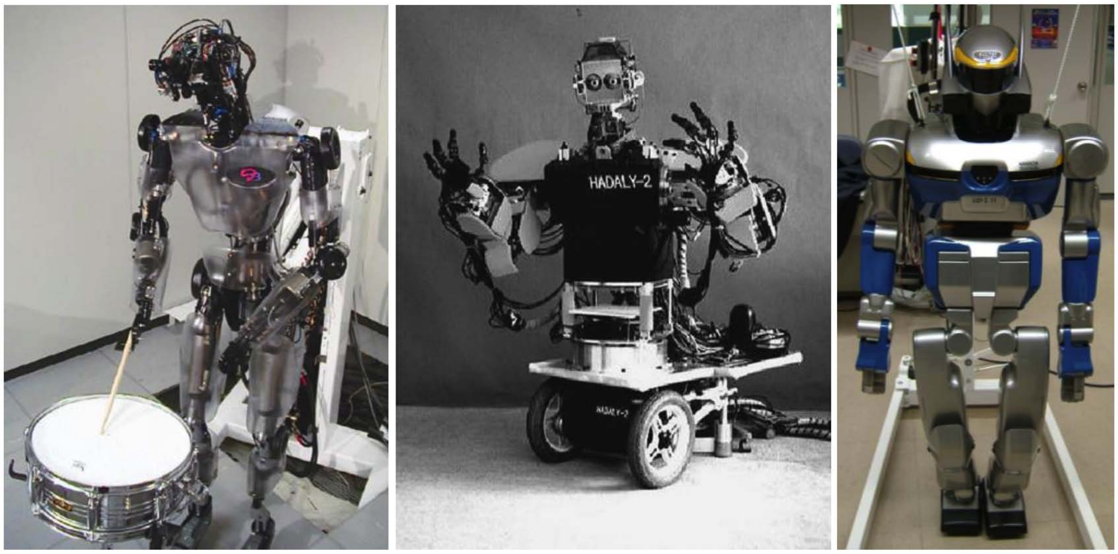


Figure 1: Complex robotic systems with high level performances: humanoid robots [1-3].

these tips are going to assist in obtaining structures with suitable mass and accurate performances. In fact, the proposed approach also provides a strategy that generates robust and compact mechanism for robot platforms. Note the proposed guidelines are related to each other in the development of proper solutions for the mechanical structure.

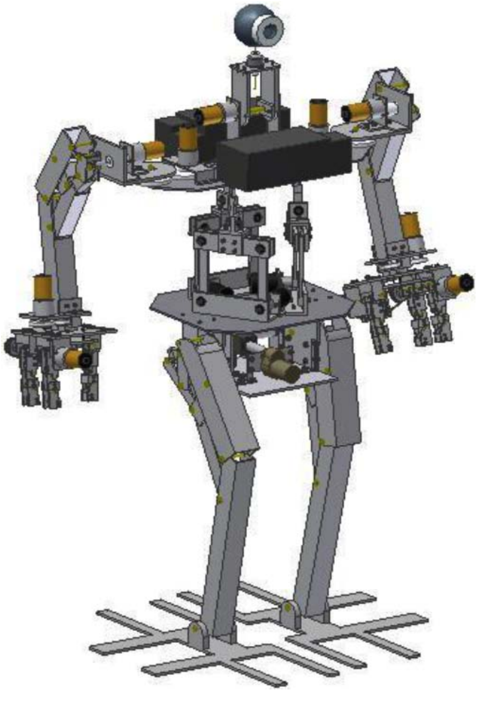


Figure 2: A 3D-CAD model of a proposed mechanical structure for a novel humanoid robot [4].

2.1. Material Selection

The materials used for the mechanical structure of robot platforms are typically aluminum, steel and titanium alloys, [1-3]. These typical materials present high density with respect to emerging materials with lower density and suitable mechanical properties, as listed in Table **1**. These emerging materials have been used in other applications with successful results, such as Al7075 for defense; cast magnesium for automotive; and Peek as well as Titanium Gr. 5 for aerospace. The main idea is to substitute the materials of some mechanical components by materials with lower density and same strength.

Table 1: Low Density Materials with Suitable Mechanical Properties [5]

Material	Density	Yield Strength	Young's Modulus
Al 7075	2.81 g/cm^3	503 MPa	71.7GPa
Titanium Gr. 5	4.43g/cm^3	880 MPa	113.8 GPa
Cast Magnesium	1.8 g/cm^3	75-200 MPa	42 GPa
PEEK	1.32-1.52 g/cm^3	100-230 MPa	4-24 GPa

For example, a piece made of steel can be made of Al 7075 (both materials have same strength but aluminum has almost a quarter of the steel density). Similar, for pieces with high stress requirements, Titanium Gr. 5 can be a feasible choice instead of high strength steels. In fact, the density of Titanium is about the half of the high strength steel with almost the same strength.

Magnesium used to be a material with very low density but low strength too. Nevertheless, a new technique for the magnesium production by casting

Table 2: Survey of Robotic Hands [8-12]

Name	Barret Hand	DIST Hand	Robonaut Hand	DLR Hand II	Ultralight Hand	Gifu Hand	Shadow Hand	UB Hand III
Brand	Barret Tech	Unv. of Genova	NASA	DLR	Centro de Inv. Karlsruhe	Unv. Gifu	Shadow Corp	Unv. of Bologna
Country	USA	Italy	USA	Germany	Germany	Japan	UK	Italia
Year	1997	1998	1999	2000	2000	2001	2004	2004
Fingers	3	4	5	5	5	5	5	5
Actuation	Elec.	Elec.	Elec.	Elec.	Hyd.	Elec.	Pneu.	Elec.
DOF	4	16	14	13	13	16	24	16

provides alloys with higher strength that can be used in application with high stress requirements. Similar, PEEK is a polymer with higher strength than other polymers but same density. The strength of both materials is similar to a commercial aluminum alloys but the density is about the half, as shown in Table **1**. Therefore, some robot parts and components can be built with these novel materials for generating lightweight mechanical structures.

2.2. Features for the Mechanical Structure

A robot platform can be conceived by using industrial components with a robust simple mechanical design and easy-operation through flexible programming. Those characteristics can be achieved in a very practical way by using components from market into a suitable design for the whole system. The use of such kind of components may decrease the complexity of design. Therefore, commercial components are a very good expedient for reducing the weight and time of designing. The mechanical design of mechanism architectures can be conceived in such a way that links and transmissions are of easy machining and assembling. Nevertheless, such design will yield to a robot with limited capability both in mechanical versatility and programming flexibility. But in general, it can be thought these robots may still have interesting performances for mobility, manipulation, and autonomous operation that are useful in many outdoor and indoor applications.

Table **2** lists some successful mechanical hands available in the market from universities and research institutes around the word. These platforms present complex mechanical structures with high weight and cost. The proposed approach is to use feasible systems with no-complex designs and reduced number of actuators, as the prototypes shown in Figure **3**. In particular, Figure **3a** shows the last version of LARM hand prototype that has been designed and built, [6]. This prototype has fingers with approximately the same sizes of human fingers. Each finger has one DOF that is actuated by a DC motor, in which gear train transmits

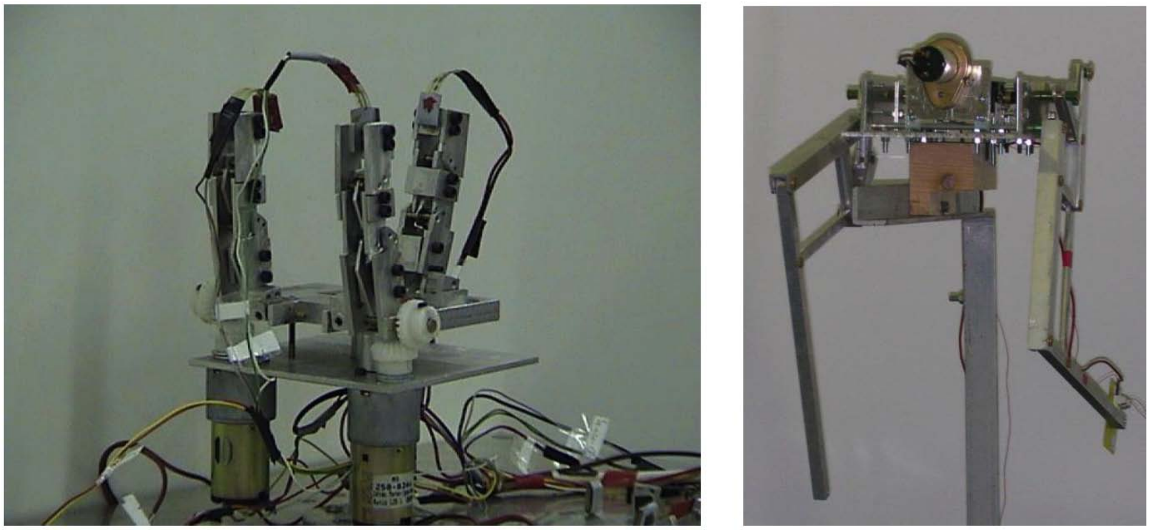

a **b**

Figure 3: Robotic systems with suitable mechanical structure: (**a**) LARM Hand [6]; (**b**) a biped robot [7].

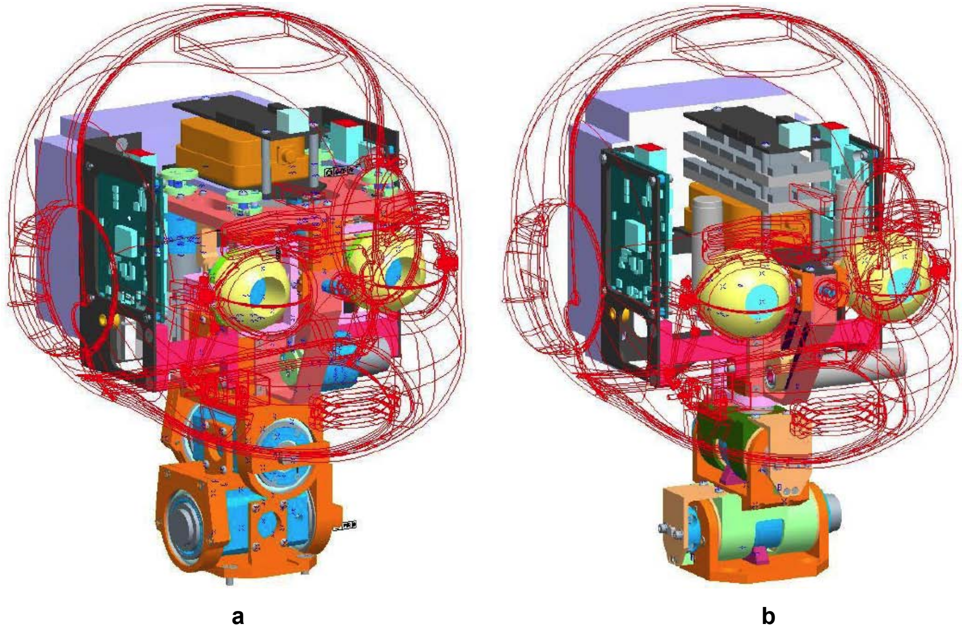


Figure 4: Structure of the head sub-system of the humanoid robot iCub [13]: (**a**) a mechanical design; (**b**) weight reduced design.

the motor actuation to the finger. An articulated mechanism drives the finger movement. The driving finger mechanism is a series of a two-crossed four-bar linkage mechanism. This mechanism is robust, low-cost, easy-operation and it can be embedded on the body of the finger that gives a compact design.

Commercial components of aluminum alloy have been used for manufacturing the prototype since they give a lightweight structure. Similar, Figure **3b** shows a leg prototype that has been designed and built. This biped robot has an articulated structure of Chebychev-Pantograph mechanism with one DOF, [7]. It is clear this mechanical structure is lighter than the biped robot of Figure **1**, but the versatility of the prototype is reduced too. Nevertheless, the robots of Figure **3** present basic operations, such as cylindrical grasping and straight walking, which can be performed successfully.

The proposed approach can be also applied to complex designs of platforms with high level operation, for example the head sub-system of the iCub humanoid robot, [13]. Figure **4** shows 3D-CAD models of two designs with different mechanical structure. In this case, the mechanical parts of the neck and eye mechanisms have been designed for obtaining in both the same performances but improving weight. Note the structure of Figure **4b** presents features that provide smaller dimensions and simplify the structure of Figure **4a**, but the same mechanical characteristics should be achieved. Another option is to keep the mechanical design of Figure **4a** but choosing proper materials with low density.

The commercial components with suitable features can be selected for the new designs. The market competition continues and novel products with better characteristics are available. Smaller dimensions, new materials and new manufacturing processes are significant characteristics for new components that the market is continuously providing.

2.3. Synthesis of Mechanism

The synthesis of the robot mechanics should be addressed to obtain mechanisms with reduced number of links and DOF (Degrees of Freedom) as well as lightweight. Figure **5** shows the kinematic *scheme* and simulation of the robot prototypes of Figure **3**. This previous task should be carried out in order to obtain suitable mechanical structures. In fact, the performance of a mechanism must be verified before construction for ensuring the effectiveness of the proposal. In some cases, the study of nature can be useful in order to obtain successful mechanism with suitable characteristics [14], for example in the design of anthropomorphic and zoomorphic systems.

Figure **6** shows an example of a mechanical design for easy and fast operation of a complex system such as a walking robot. In particular, Figure **6a** shows a 3D-CAD model of the walking robot that represents the first solution that has been obtained by following this

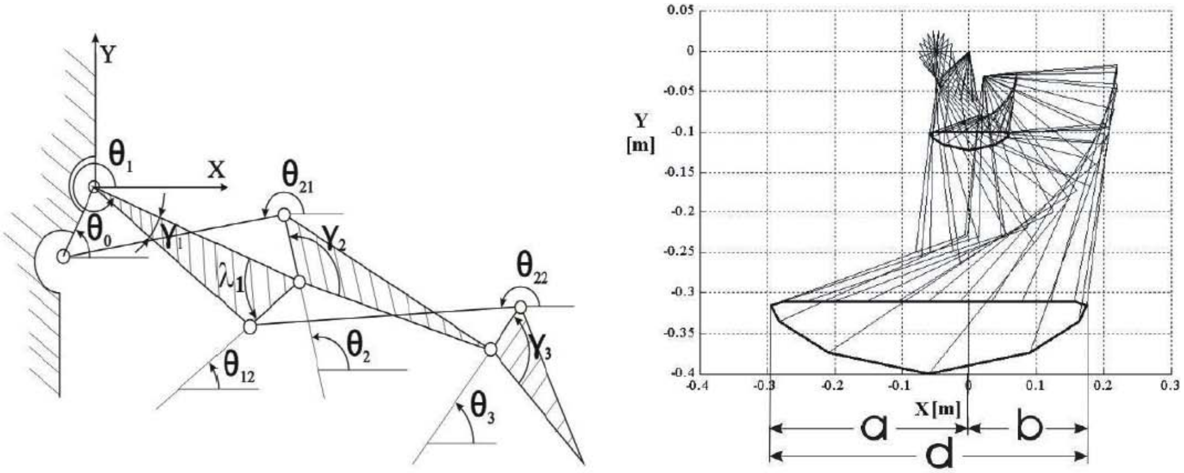
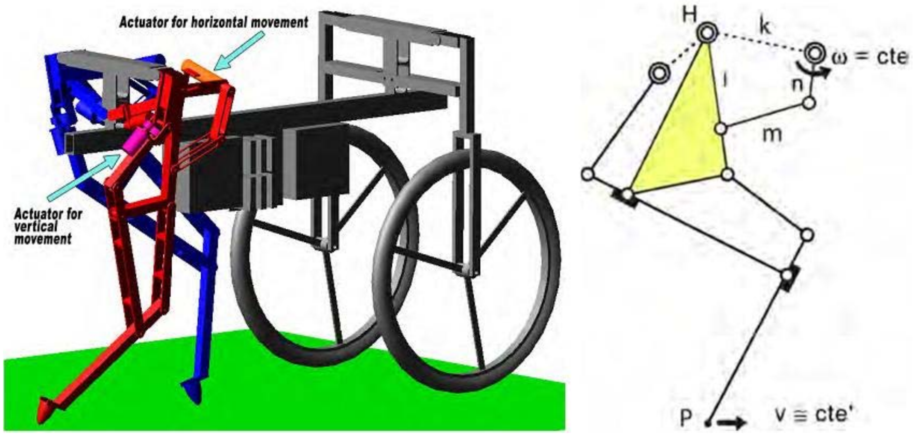


Figure 5: Kinematic *scheme* and simulation of the robotic hand and biped of Figure **3**: (**a**) kinematic *scheme* of the 1-DOF-articulated robotic finger [14]; (**b**) kinematic simulation of the mechanical leg [7].

procedure. In the hybrid robot of Figure **6a** the problem of lateral stability was disregarded by adding two rear wheels instead of back legs. Therefore, the robot is composed of two articulated legs, as front legs, and two passive wheels, as back legs. These rear legs are fixe for movement on flat terrain but they will be controlled in future to overcome obstacles [15]. Figure **6b** shows a *scheme* that improves the performance of previous *scheme* by adding a new four bar mechanism. The new four bar mechanism has been synthesized as a function generator by using four-point Freudenstein equations.

The points in the function generation have been chosen in order to obtain a constant velocity of point P in the central part of the trajectory, specifically within the central 600mm, that is the rated step length of the mechanism. Despite this rated value, the leg is capable of taking shorter or longer steps (up to 1 m). Far from the conditions in which the synthesis has been made, the trajectories are not straight lines and there is some coupling between vertical and horizontal movement. However, this coupling does not interfere with the good execution of the step in normal operation.

In other way, the synthesis of complex structures with high numbers of links and DOF is not necessary because generally each links is directly driven by each actuating DOF. The modern research involves the participation of experts in different fields composing a multidisciplinary group for the development of complex systems like humanoid robots. Some mechanical solutions applied to the structure design can interfere with the proper operation of certain complex systems. These solutions can be successful from the mechanical point of view but their characteristics cannot be proper in specific applications. Therefore, feedback from experts of other research lines is necessary for mechanical designers.



a b

Figure 6: A hybrid mobile robot [15]: (**a**) a 3D-CAD model; (**b**) Kinematic *scheme*.

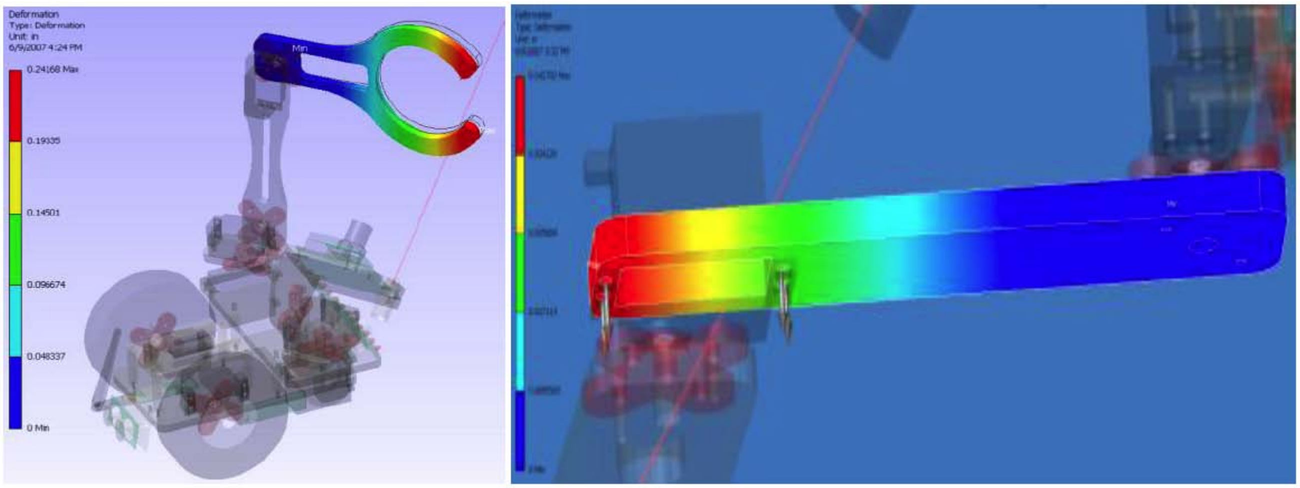


Figure 7: Finite element analyses of a mobile robot [16].

2.4. Structural Analysis

Beside of a proper material selection, features for the mechanical structure should be sized by using the results of structural analyses like FEA (Finite Element Analysis). Therefore, the thickness of the mechanical pieces can be reduced as much as possible down to dimensions that can support the stress generated during actuation. Factors of security are necessary to be considered in the analysis for ensuring the structure resistance in practical operation. Figure **7** shows an example of a structural analysis developed for a mobile robot. In particular, the end-effector and robot links have been studied in order to check the resistance to the reaction forces generated. The results present computed values of stress below the strength of the selected materials.

FEA can also be useful in order to prevent some problems in the structure, such as vibrations and thermal transfer. As much as necessary analyses should be developed before the construction of prototypes in order to avoid mistakes in the robot design. In proposed approach, the weight reduction is presented as a procedure that generates successful mechanical designs.

2.5. Actuating Joint Design

The actuating joints of complex robotic systems, like humanoid robots, can be improved in terms of weight and dimensions by taking advantage of the mechanical structure itself. In fact, the actuators of some robotic platforms are electrical motors that are connected directly to the joints for driving the links, [1]. Nevertheless, selecting frameless commercial components and designing proper mechanical pieces, motors can be embedded in the joint structure. Similar, other joint equipments and instrumentations, like sensors and gearboxes, can be embedded too.

Figure **8** shows an example of a robotic joint with the motor, equipment and instrumentation embedded in

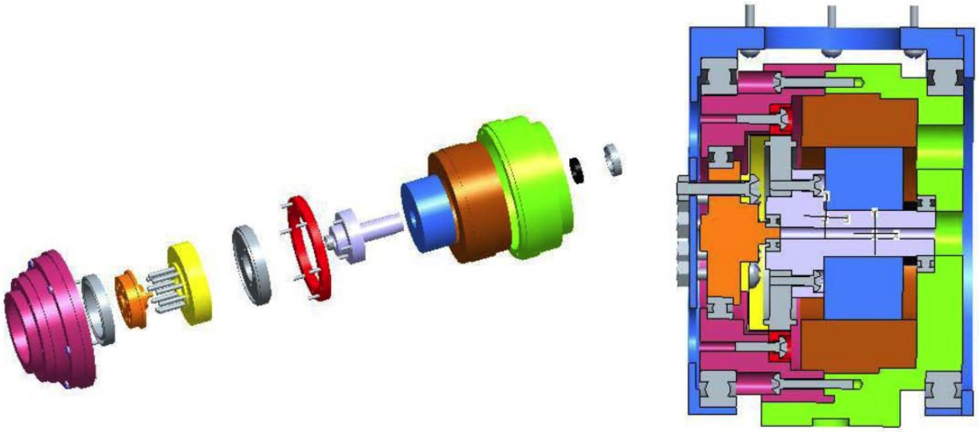

a **b**

Figure 8: A robotic joint design: (**a**) explosion view; (**b**) cross-section.

Figure 9: Arm sub-system of MAFRED robot [17].

the structure. In this case, brushless and frameless electrical motors have been selected for the design. Gearboxes of Harmonic Drive have been used for increasing the output torque with lightweight and low backlash. Mechanical parts have been designed for locating the motors as well as harmonic drives and connecting each other.

In the following section 3, the actuating joints of a robotic arm have been designed by this procedure. The process began from the improvement of a built prototype, in which the weight reduction by a proper joint design is recognized.

Another example of improvement by joint design has been the neck structure of the iCub head of Figure **4**. In this case, gearboxes are not necessary because the low torque required, but motors and bearing are included in the joint structure. Moreover, the mechanical pieces provide the connection between joint in a compact and robust way.

Note this design philosophy is difficult to apply to articulated robots like those of Figures **3** and **6**. In this case, the mechanical structure already takes full advantage of mechanics and improvements in joint design are not possible. In fact, trying to include the actuator in the joint structure can make the design more complex instead.

3. ILLUSTRATIVE EXAMPLE: HOW TO REDUCE MASS

Figure **9** shows an overview of the mobile robot MANFRED [17], which has a lightweight arm for reducing the inertia and increasing safety. Using anthropomorphic arms located laterally is now the most adopted solution for mobile robots. In la late past, the mobile robots were composed of industrial robotic arms, which structure and high weight were not the best solution for this application. Moreover, the control unit increases dramatically the weight of the total platform. Thus, more power consumption is required for increase the robot autonomy.

The mobile robot of Figure **9** includes the light-weight arm manipulator and the electronic components in the body of the structure. The robot control is executed by using drivers and a main board instead of the control units of the industrial manipulators. One aim of reducing the weight of the mechatronical system is to increase the robot stability during lateral manipulations. Another aim is obtaining a robust and compact design.

The built mobile model of MANFRED presents acceptable payload capacities that provide successful manipulation tasks. Moreover, the total weight of the structure is lower than the commercial industrial

Table 3: Survey of Lightweight Robotic Arms [18-21]

Name	Brand	Country	Year	Actuation	DOF	Payload	Weight
DLR III	DLR /KUKA	Germany	2007	Elec.	7	13.5 Kg	13.5 Kg
DEXARM	ESA	Italy	2004	Elec.	7	0 – 500 Kg @ g = 0 m/s^2	20 Kg
N/A	Robot Alive	India	2009	Elec.	6	1.5 Kg	10 Kg
PANDI-2	Orebro Univ.	Sweden	2004	Elec.	6	1 Kg	10 Kg
Lynx 6	Lynxmotion	China	2009	Elec.	6	85 gr	0.6 Kg
IRB-120	ABB	Switzerland	2009	Elec.	6	3 Kg	25 Kg
RV-2AJ	Mitsubishi	Japan	2009	Elec.	5	2 Kg	17 Kg
TX40	Stäubli	Switzerland	2009	Elec. and Pne.	6	2.3 Kg	27 Kg

manipulators available in the market. The workspace of the arm is quite similar to the human once, thus the design allows flexibility for the manipulation tasks with 6 degrees of freedom. The main characteristics of the arm sub-system are:

Degrees of freedom: 6,

- Total weight: 18 Kg,
- Payload: 60 N,
- Length: 1205 mm.
- Workspace: 955 mm
- Maximum velocity: 180 °/s

A new design for the arm manipulator of MAFRED has been developed in order to improve the characteristics of the current robot. Therefore, 7 DOF are proposed for the mechanical structure since the characteristics of the human mobility can be achieved. Including another actuating joint represents an extra challenge for weight reduction because the mass should be gone down even if the number of components is increased.

Weight reduction is one of the main goals of the work but the stiffness of the structure should be ensured for reducing the complexity of the control architecture. Lower mass yields lower inertia that provides better safety for human-robot interaction. A new architecture with 7 DOF requires special care in the design for keeping the same weight of the current robot. Therefore, the proposed approach has been applied during the design process. The following milestones have been proposed for the new design:

- Anthropomorphic design,
- 7 degrees of freedom,
- Low level control architecture,
- Lightweight,
- Compactness and robustness.

Table lists the main characteristics of successful and lightweight robotic arms. The proposed design has been developed in order to obtain similar characterristics of these manipulators.

The new arm design began from the analysis of the current structure in terms of mass reduction. The first step has been the study of the mechanical parts for reducing dimensions. The structural analysis of the most stressed part has been developed with the stress result of 14.2 MPa during the manipulator of 60 N of payload. The part has been made of an aluminum alloy with 150 Mpa of yield strength, thus a factor of security of 10.6 has been assumed in the design. The second step is the selection of a low density material. The proposal is to use the aluminum alloy 7075 with yield strength of 500 Mpa. Therefore, assuming the same factor of security of 10.6, the computed stress of the most stressed part has been 47.2 MPa by reducing the thickness from 8 mm down to 2.4 mm. This represents a reduction of 60% in the volume of the mechanical parts.

The weight of the mechanical parts of the current structure can be computed by subtracting the mass of the commercial components and cables to the total mass. The weights of the components and cables have been:

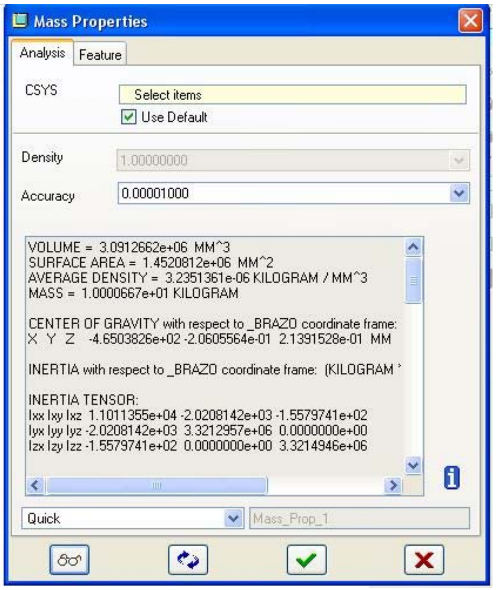
- Electrical motors: 4.5 Kg,
- Gearboxes: 3.45 Kg,
- Bearings: 0.45 Kg,
- Hardware: 0.5 Kg,
- Cables: 1.1 Kg

Since total weight of the current arm is 18Kg, the weight of the mechanical parts has been computed as 8 Kg. For an aluminum density of 2700 Kg/m3, the volume of the mechanical part has been $0.003m^3$ for 8Kg of mass. Assuming a volume reduction of 60%, the volume and the weight of the mechanical parts of the new arm were $0.0018m^3$ and 4.9 Kg, respectively. A total reduction of 3 Kg has been obtained by using the new aluminum alloy 7075.

A third step has been the new motors selection. Since the weight of the mechanical parts has been reduced, smaller electrical motors can be used. The current arm uses 4 types of Kollmorgen motors, in which the 01812 is the biggest and the most powerful actuator. The current robotic joints include a gearbox of harmonic drive with a reduction ratio of 1/160 and 75% of efficiency. The output torque of the biggest robotic joint of the current prototype is 146.4Nm. Assuming a payload of 60N, 5 Kg of the weight of the mechanical parts, and the same weight for the electronic components and cables; the required output torque of the biggest robotic joint has been computed as 129Nm for the new arm. Since the required torque has been reduced in 14 Nm, the smaller motor can be used, for example the Kollmorgen 01811 frameless.

A fourth step has been the selection of a new gearbox according to the new motors and improving performance. Ultra-thin harmonic drives have been selected with the same reduction ration of 1/160 and 75% of efficiency. Therefore, the output torque of the new biggest joint has been 102.7 Nm. The total mass of the new motors and gearboxes have been 2.9 Kg. Since the total DOF has been proposed as 7, the weight of the extra robotic joint should be included in the computation of the mass of the new arm. The proposed joint has been the roll of shoulder, which provides manipulation in the area in front of the mobile robot. This joint is composed of a Kollmorgen motor 01213 of 0.34 Kg and an ultra-thin harmonic drive of 0.13 Kg. The weight of the mechanical parts has been assumed as the same of the other robotic joints of 0.83 Kg. Finally, the total mass of the new arm can be computed addend the new masses of mechanical part, motors, gearboxes, bearings, hardware, cables and the extra joint. Therefore, the total mass of the new proposed arm has been computed as 10.3 Kg.

The output torque of the biggest robotic joint should be computed in order to verify the required torque for the new mass and dimensions of the mechanical structure. The new length of the robot arm has been proposed as 0.7 m because it ensures a feasible workspace without interference between arm and trunk. Giving a new mass of 103 N, new length of 0.7 m and 60 N of payload, the computed required toque for the biggest robotic joint has been 78.1 Nm, which is lower



CSYS: Select items

☑ Use Default

Density: 1.00000000

Accuracy: 0.00001000

```
VOLUME =  3.0912662e+06  MM^3
SURFACE AREA =  1.4520812e+06  MM^2
AVERAGE DENSITY =  3.2351361e-06 KILOGRAM / MM^3
MASS =  1.0000667e+01 KILOGRAM

CENTER OF GRAVITY with respect to _BRAZO coordinate frame:
X  Y  Z   -4.6503826e+02 -2.0605564e-01  2.1391528e-01  MM

INERTIA with respect to _BRAZO coordinate frame:  (KILOGRAM *

INERTIA TENSOR:
Ixx Ixy Ixz  1.1011355e+04 -2.0208142e+03 -1.5579741e+02
Iyx Iyy Iyz -2.0208142e+03  3.3212957e+06  0.0000000e+00
Izx Izy Izz -1.5579741e+02  0.0000000e+00  3.3214946e+06
```

Quick

Mass_Prop_1

Figure 10: New design for the arm sub-system of MAFRED robot.

that the output of the biggest joint proposed (102.7 Nm). Therefore, the effectiveness of the proposed approach has been validated for a new arm with 7 DOF. A commercial boar Turbo PMAC2 PCI is proposed for the control of the 7 motors because it has the capability of control of 4 to 32 shafts.

Figure **10** shows a 3D-CAD model of the proposed design for the new arm sub-system of MANFRED robot with the mechanical characteristics. The structure has been divided in three main groups of actuating joints, such as shoulder, elbow and wrist, joined by links made of carbon fiber. The shoulder group is composed of pitch of shoulder, yaw of shoulder and roll of upper arm; the elbow group is composed of pitch of elbow and roll of forearm; and the wrist group is composed of pitch and yaw of wrist. The mechanical structures of the joint groups and links have been designed considering the path of the electrical cables through the body of the pieces.

The robotic joints of the new serial manipulator are mainly composed of two types of assembly, as shown in Figure **11**. One joint assembly provides the link rotation around the axial axis, Figure **11a**, and the other assembly provides the link rotation around the transversal axis, Figure **11b**.

Note the internal structures of both joints are composed of the same mechanical parts and components, such as motor rotor, motor stator, harmonic Drive, bearings, screws, shafts and housings.

a

CSYS: Select items

☑ Use Default

Density: 0.00000271

Accuracy: 0.00001000

```
VOLUME =  3.2605670e+05  MM^3
SURFACE AREA =  1.3017037e+05  MM'
AVERAGE DENSITY =  3.2833536e-06 K
MASS =  1.0705594e+00 KILOGRAM

CENTER OF GRAVITY with respect to _P
X  Y  Z   -7.1101125e+00  0.0000000e+

INERTIA with respect to _PITCH coordina
```

Mass_Prop_1

b

CSYS: Select items

☑ Use Default

Density: 1.00000000

Accuracy: 0.00001000

```
VOLUME =  5.3866484e+05  MM^3
SURFACE AREA =  2.2494808e+05  MM'
AVERAGE DENSITY =  3.4110172e-06 K
MASS =  1.8373950e+00 KILOGRAM

CENTER OF GRAVITY with respect to _Y
X  Y  Z   -1.3620312e+01  4.4260372e+

INERTIA with respect to _YAW coordinat
```

Mass_Prop_1

Figure 11: Robotics joints of the new arm sub-system: (**a**) pitch of shoulder; (**b**) yaw of shoulder.

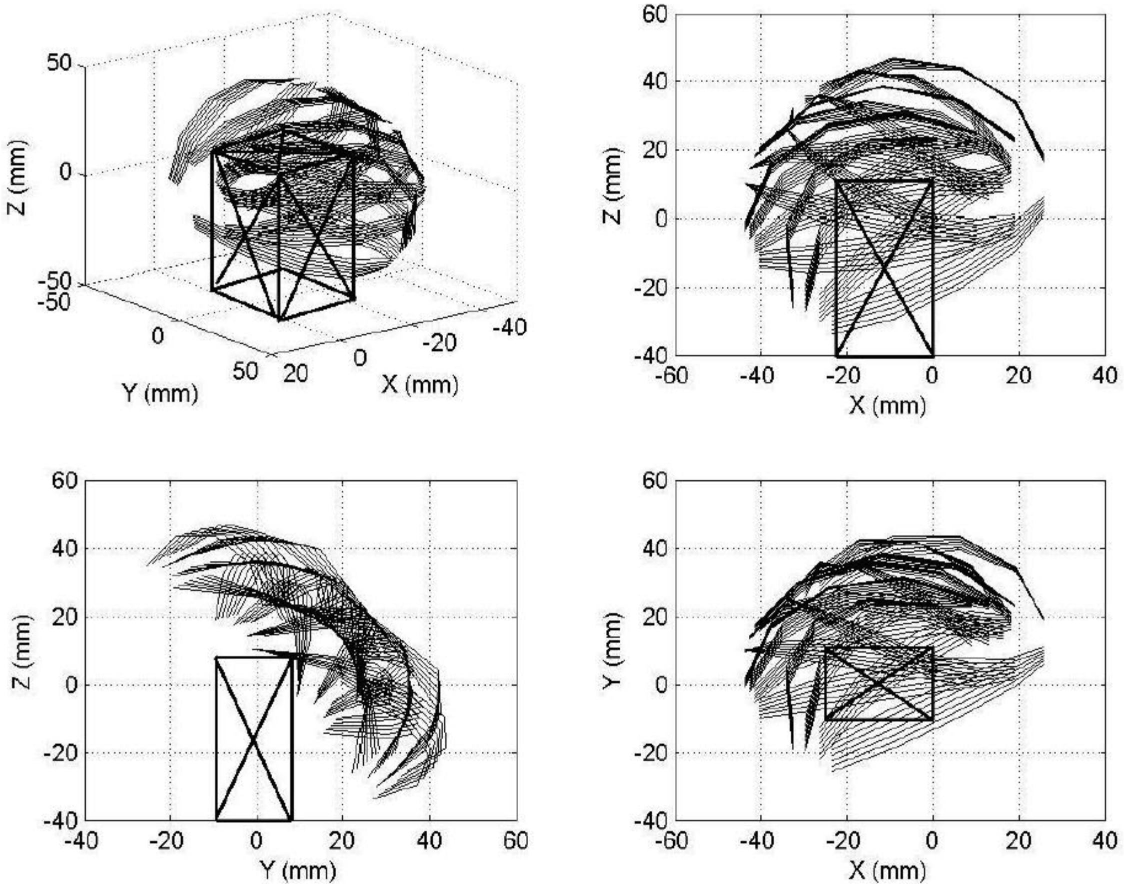


Figure 12: Kinematic simulation of the new robotic arm.

The main difference between both assemblies is that the output shaft of the joint of Figure **11a** is connected directly to the link and in the joint of Figure **11b** the link is connected through a mechanical interface. Mechanical characteristics of both robotic joints can be recognized in Figure **11**.

4. NUMERICAL VALIDATION OF PROPOSAL

The weight reduction represents a significant change in the structure of mechanical systems. Therefore, numerical validations of the new designs are necessary in order to avoid failures of pieces, components and operations before the construction of real prototypes. For the new robotic arm of Figure **10**, kinematic and dynamic analyses are proposed. Static and structural analyses have been performed with successful results, as reported in section 3.

Figure **12** shows the results from the kinematic analysis of the proposed arm. In order to check the workspace of the serial manipulator, the kinematic equations have been formulated in Matlab including 7 DOF and a distance of 0.7 m from the joint shaft of pitch of shoulder to the end-effector. The lines of the plots of Figure **12** represent the trajectories followed by the end-effector for all possible configurations of the robotic joints.

The cube of Figure **12** represents the trunk subsystem of the mobile robot. Kinematic simulations of the arm movement with the elbow pitch at 90° have been developed as part of the kinematic analysis. Note that the additional joint for the elbow pitch provides a wide range of manipulation of the front of the MANFRED body without interferences, as shown in the plot of the Y-Z plane of Figure **12**. The plots of the planes X-Y and X-Z of Figure **12** show the high capability of the arm movement for manipulation around the robot body. Moreover, Figure **12** shows a 3D view of the workspace that allows finding out the extended manipulation range of the new robotic arm respect the previous design of Figure **9**.

Dynamic simulations of the new arm operation have been developed by using the 3D-CAD model of Figure **10**. In dynamic simulations, the payload of 60 N has been included in the tip of the whole structure. Figure **13** shows the results of the simulations in which the time table of the maximum required torques of joint

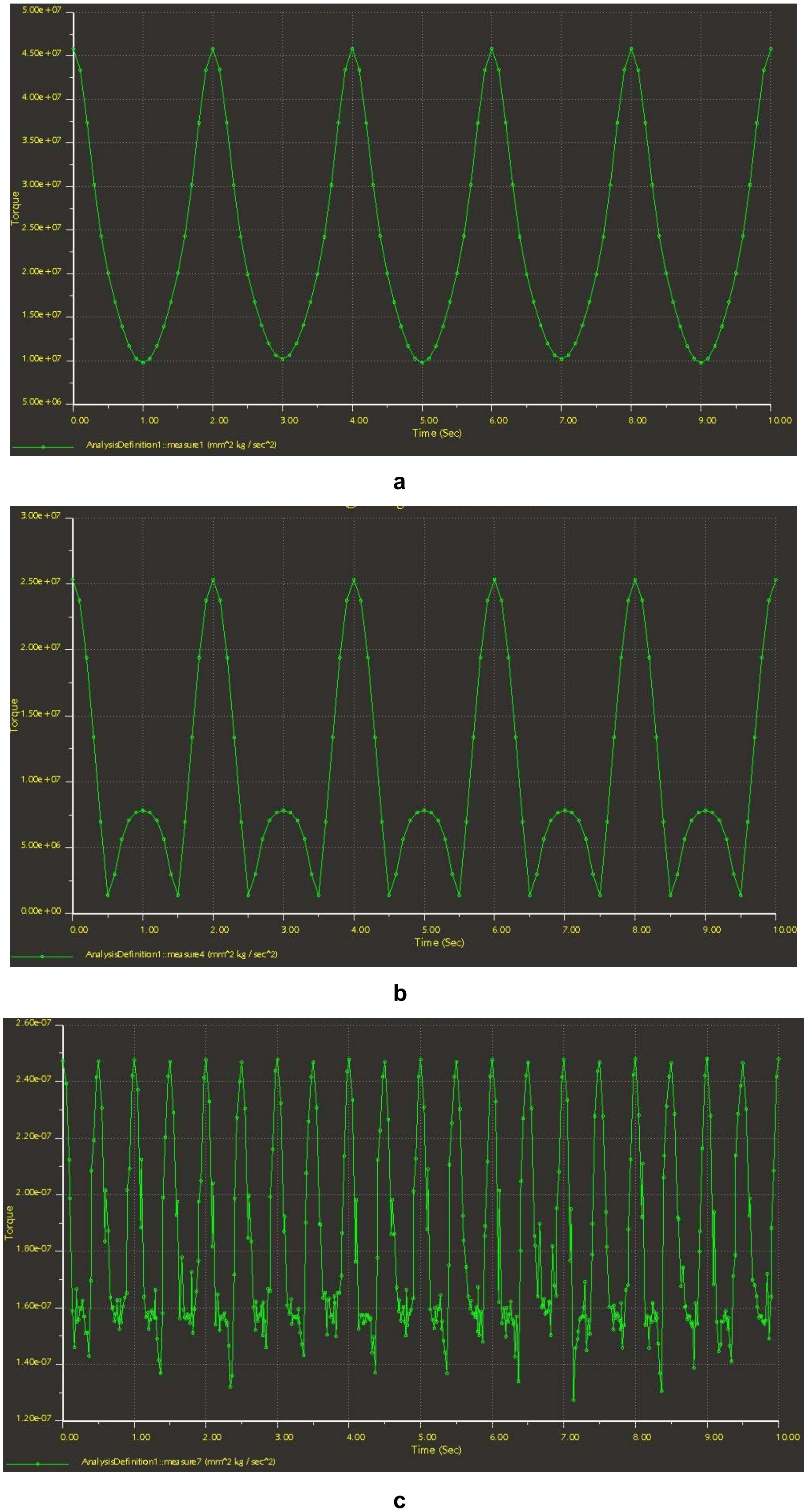


Figure 13: Results of dynamic simulation of the new arm operation: (**a**) maximum torque of the shoulder joints; (**b**) maximum torque of the elbow joints; (**c**) maximum torque of the wrist joints. (Toques in mm^2 Kg / sec^2).

groups are plotted. In particular, Figure **13a** shows the torque of the shoulder complex; Figure **13b** shows the torque of elbow; and Figure **13c** shows the torque of wrist. The values of the maximum torques have been computed to be about 45 Nm for the shoulder joints and about 25 Nm for the elbow and wrist joints. The output torques provided by the proposed Kollmogen motors are bigger than the computed required values in the dynamic simulations, as reported in section 3.

The results of the analyses report suitable values of robot workspace and output torques of joints. The characteristics of the new arm design fulfill the requirements of the robot operation. Therefore, the effectiveness of the proposed approach of weight reduction has been checked. The obtained design presents a robust mechanical structure in which the actuated joints are located in groups of assemblies joined by rigid links.

5. CONCLUSION

A novel approach for the weight reduction of complex mechanical structures has been illustrated with practical examples. The paper is mainly composed of two parts: reduction of the complexity of the mechatronical system and changes in the design of the mechanism. Novel systems with articulated mechanisms represent both easy-operation and lightweight solutions for the robotic platforms. The versatility of these systems is reduced with respect to other successful prototypes. The proposed machines can perform suitable basic operations useful in practical applications. Moreover, the proposed approach of weight reduction can be applied to complex systems that require mass reduction for improving performance. New components available in the market with lower volume and novel characteristics can be used. Mechanical parts can be studied in order to reduce volume and change the material. A design strategy should be followed based of feed backs from the results of static and structural analyses.

The proposed method has been validated with the design of a new robotic arm. The design process has begun from the analysis of a previous prototype for changing the mechatronical system in order to reduce weight and improve performance. The new solutions have been the use of new motors and gearboxes; reducing of the volume of the mechanical parts by developing structural analyses; including a kinematic chain of 7 DOF; and performing a mechanical design for a compact and robust structure. The validation of the new design has been developed by computing the kinematics and dynamics of the mechanism. In fact, the result of any design approach should be validated by carrying out mechanical and structural analyses. The workspace of the proposed serial manipulator has been obtained, validating the high manipulation capability of the mechanical structure. The required output torques of the robot joints have been computed by using dynamic simulation of the arm operation. The torques given by the designed joints fulfill the requirements for a proper robot operation. Further works attend the construction of the proposed new arm for practical application in the MANFRED platform.

REFERENCE

[1] HRI. Waseda University-Humanoid Robotics Institute. Second Edition. Japan: Waseda University 2001.

[2] AIST. Robot Technology at AIST. Japan: National Institute of Advanced Industrial Science and Technology 2004.

[3] Hirukawa H, Kanehiro F, Kaneko K, Kajita S, Fujiwara K, Kawai Y, Tomita F, Hirai S, Tanie K, Isozumi T, Akachi K, Kawasaki T, Ota S, Yokoyama K, Handa H, Fukase Y, Maeda J, Nakamura Y, Tachi S, Inoue H. Humanoid Robotics Platforms Developed in HRP. Robotics and Autonomous Systems 2004; 48 (4): 165-175. http://dx.doi.org/10.1016/j.robot.2004.07.007

[4] Nava Rodriguez NE, Carbone G, Ceccarelli M. Simulation Results for Design and Operation of CALUMA, a New Low-cost Humanoid Robot. International Journal Robotica 2008; (26): 601-618.

[5] Metals Handbook. Properties and Selection: Nonferrous Alloys and Special-Purpose Materials. 10th Edition. ASM International 1990.

[6] Ceccarelli M, Nava Rodriguez NE, Carbone G. Design and Tests of a Three Finger Hand with 1 Dof Articulated Fingers. International Journal Robotica 2006; 24: 183-196. http://dx.doi.org/10.1017/S0263574705002018

[7] Ottaviano E, Lanni C, Ceccarelli M. Numerical and Experimental Analysis of a Pantograph-Leg with a Fully-Rotative Actuating Mechanism. Proceeding of World Congress in Mechanism and Machine Science, Tianjin 2004; 1537-1541.

[8] Caffaz A, Bernieri S, Cannata G, Casalino G. The DIST-HAND robot. Intelligent Robot and System 1997; 3.

[9] Butterfass J, Grebenstein M, Lui H, Hirzingher G. DLR-Hand II: next Generation of a Dextrous Robot Hand. International Conference on Robotics and Automation 2001; 1: 109-114.

[10] Schulz S, Pylatiuk C, Bretthauer G. A New Ultralight Anthropomorphic Hand. International Conference on Robotics and Automation 2001; 3: 2437-2441.

[11] Kawasaki H, Komatsu T, Uchiyama K, Kurimoto T. Dexterous Anthropomorphic Robot Hand with Distributed Tactilesensor: Gifu hand II. International Conference on System, Man and Cybernetics. Tokio 1999; 2: 782-787.

[12] Lotti F, Tiezzi P, Vassura G, Biagiotti L, Palli G, Melchiorri C. Development of UB Hand 3: Early Results. International Conference on robotics and Automation 2005; 4488-4493.

[13] Nava Rodriguez NE, Tikhanoff V, Metta G, Sandini G. Kinematic and Dynamic Simulations for the Design of ICub Upper-Body Structure. Proceeding of the 9th Biennial ASME Conference in Engineering System Design and Analysis ESDA. Haifa-Israel 2008; paper ESDA2008-59082.

[14] Nava Rodriguez NE, Carbone G, Ceccarelli M. Optimal Design of Driving Mechanism in a 1-d.o.f. Anthropomorphic Finger. Mechanism and Machine Theory 2006; 41(8): 897-911. http://dx.doi.org/10.1016/j.mechmachtheory.2006.03.016

[15] Gonzalez Rodriguez AG, Gonzalez Rodriguez A. Mobile Robots. In Nava Rodriguez N E, Ed. Advanced Mechanics in Robotic Systems. London: Springer 2010.

[16] Jiaxin Ma, Yu Zhang, Yunjun Nam, Cichocki A. EOG/ERP Hybrid Human-Machine Interface for Robot Control. IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS). Tokyo-Japan 2013; 859-864.

[17] Blanco D, Al Ansari S, Castejón C, López Boada B, Moreno L. Manfred: Robot Antropomórfico De Servicio Fiable y Seguro Para Operar En Entornos Humanos. Revista Iberoamericana de Ingeniería Mecánica 2005; 9(3): 33-48, 2005.

[18] Albu-Schaffer A, Haddadin S, Ott Ch, Stemmer A, Wimbock T, Hirzinger G. The DLR Lightweight Robot: Design and Control Concepts for Robots in Human Environments. Industrial Robots 2007; 34(5): 376-285. http://dx.doi.org/10.1108/01439910710774386

[19] Rusconi A, Magnani P, Gonzalez Lodoso J F, Campo P, Chomicz R, Magnani G. Design and Development of an Integrated Joint for the Dextrous Robot Arm. Proceedings of the 9th ESA Workshop on Advanced Space Technologies for Robotics and Automation 2006.

[20] Halliday A. NID techno start-up promotes robotic arm as learning tool for students. Indian Express.com 2009.

[21] Qtiash I A, Wallberg M. Prototyping a Lightweight Robot Arm. Ph. D. Thesis. Orebro University 2004.

Received on 08-09-2014 Accepted on 24-09-2014 Published on 18-11-2014

https://doi.org/10.15377/2409-9694.2014.01.01.4