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Simulation-Based Energy Efficiency Analysis of Composite Material Robotic Arms

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Research Article

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Abstract

actuator energy of repetitive robotic motion cycles is controlled by link inertia, which is proportional to material density. The paper measures the energy efficiency of the replacement of the Aluminium 6061-T6 (2700 kg/m^3) links by unidirectional CFRP (UD-CFRP, 1600 kg/mm^3) on a 2-DOF planar robotic arm. The arm was created in AutoCAD; mass properties were copied using the MASSPROP and loaded into MATLAB. Adequacy Structural adequacy was checked analytically no finite element analysis was conducted. The equations of lagrangian dynamics provided the equations of joint torque which were then integrated with trapezoidal cycle of 2 s to determine mechanical energy per cycle. FRP arm smaller CFRP arm decreased the peak Joint 1 torque of 0.01085 Nm to 0.00643 Nm (− 40.79%), and the energy per cycle of 0.1382 J to 0.0818 J (40.78%), which is in agreement with the analytical density-ratio prediction of 40.74%. The given saving is a lower bound since CFRP was conservatively assumed to be 70 Gpa (equivalent to aluminium). A 40.78% reduction of energy per cycle by actuator substitution is achieved by changing the actuator only, and maintaining the trajectory.

1. INTRODUCTION

The use of energy by industrial robotic manipulators has emerged as a critical operation and sustainability issue as the scale of deployment continues to increase in the world. A considerable portion of actuator energy is dissipated on link inertia instead of doing useful payload work in repetitive cycles of motion [10]. Since the mass of the links represents inertia, and the mass of the material represents the same, identifying a material with a lower density is one of the simplest interventions the designers of the robotic system can give (because the mass of the material is directly proportional to its density). The link construction in the robotic construction has over the decades been dominated by aluminium 6061-T6 (2700 kg/ m^3)) due to its machinability, resistance to corrosion and the well-defined fatigue behaviour [3],[6]. But its density gives it an inertial penalty: heavier end actuators need increasingly larger proximal actuators, giving rise to an exponentially growing mass-energy cascade [3]. Carbon Fibre Reinforced Polymer (CFRP, 1600 kg/ m^3) is available in 41% reduction in mass with the same geometry, which directly translates into reduced inertia of the joint, reduced torque requirement, and reduced energy per cycle [4],[8]. Nonetheless, with these well-established material properties, the question of which direct comparison needs to be made between Aluminium 6061-T6 and CFRP, within the context of a single geometric-modelling and dynamic-analysis workflow that will return the result in terms of a quantifiable percentage in terms of energy efficiency, is scarce [5]. To fill that gap, this paper will integrate AutoCAD solid modelling with MATLAB Lagrangian simulation in order to provide a self-sufficient and reproducible energy comparison of a 2-DOF planar arm. The software does not need any finite element.

2. METHODOLOGY

This study uses a simulation-based approach to evaluate the energy efficiency of a 2-DOF planar robotic arm made from Aluminium 6061-T6 and unidirectional CFRP. The arm is first modelled in AutoCAD, and

its mass properties are obtained using the MASSPROP command. These properties are then imported into MATLAB, where a Lagrangian dynamic model is used to compute joint torques and energy consumption. The results are finally compared under identical operating conditions to assess the impact of material selection.

Figure 1 shows the overall workflow of the study. The robotic arm is first modelled in AutoCAD, and its mass properties are extracted. These are used in MATLAB to compute torque and energy using a Lagrangian model with a predefined motion profile. The results are then compared to evaluate the effect of material selection.

A. AutoCAD Modelling and Arm Geometry.

In AutoCAD, the 3D solid primitives were used and a 2-DOF planer robotic arm was drawn in 3D. The size of the cross-section was 120 × 30 × 30 mm (square cross-section) of Link 1 and 100 × 40 × 25 mm (rectangular cross-section) of Link 2, allowing a maximum reach of 220 mm. Volumetric and mass properties were obtained on both links using the MASSPROP command and fed to MATLAB, both links being modelled as solid rectangular prisms. Both materials were done using the same geometry; the only difference was in density.

Table 1
Arm design parameters.

Parameter	Symbol	Value
Link 1 length	L_1	0.12 m
Link 1 cross-section	$w_1 \times \mathrm{h}_1$	30×30 mm
Link 2 length	L_2	0.10 m
Link 2 cross-section	$w_2 \times \mathrm{h}_2$	40×25 mm
Max reach	Rmax	0.22 m

B. Material Properties

Two materials were analyzed on the same geometry and loading. UD-CFRP elastic modulus was adjusted to a safe level comparable to that of aluminium (70 Gpa) to make sure that all of the energy gains come only due to the density difference, not due to any perceived stiffness advantage [8],[6].

Table 2
Mechanical properties of Aluminium 6061-T6 and UD-CFRP.

Property	Al 6061-T6	UD-CFRP
Density ρ (kg/m³)	2700	1600
Young's Modulus E (GPa)	69	70 (conservative)
Tensile Strength (MPa)	310	600 – 1500
Poisson's ratio v	0.33	0.25
Specific Stiffness (MN·m/kg)	25.6	43.75

C. The computation of mass and Inertia

Is the third step to be taken. Link volumes obtained in AutoCAD V_1 = 1.0810–4 m -3, V_2 = 1.0010 -4 m -3. Link masses follow m = ρV:

C. Mass and Inertia Computation

Table 3
Link mass comparison

Link	Volume (m³)	Al mass (kg)	CFRP mass (kg)	Reduction
Link 1	1.08×10^{-4}	0.2916	0.1728	40.74%
Link 2	1.00×10^{-4}	0.2700	0.1600	40.74%
Total	2.08×10^{-4}	0.5616	0.3328	40.74%

I = (1/3)mL^2 was calculated as the effective rotational inertia around each joint of a uniform slender beam rotating about one end. In the case of Link 1: I 1 Al = 0.001400 kg m^2 (aluminium), I 1 CF = 0.000829 kg m^2 (CFRP) --- a 40.74% decrease that is the same as the mass ratio.

D. Structural Verification Structural checks in their analysis.

Analytically, the structural adequacy was determined through cantilever bending theory; the finite element analysis was not done. At a representative 5 N tip load, the bending stress of the Link 1 was found to be 0.267 Mpa (aluminium) and 0.240 Mpa (CFRP), which is an order of magnitude less than the corresponding yield strength (276 Mpa and above 600 Mpa) and hence the structural risk is minimal on both materials. The deflection of the tips was 0.00124 mm (aluminium) and 0.00122 mm (CFRP) which is well within the operational ranges. The materials have enormous safety factors at the actual loading, and this verifies the design.

E. Lagrangian Dynamic Model

Joint torques are governed by the equation of motion τ = M(q) $\ddot{q}$ + C(q $\dot{q}$) $\dot{q}$ + G(q) which is a form of the inertia matrix, Coriolis centripetal term, and gravity. When the arm is horizontal, and planar, G = 0, and the torque is determined solely by $\mathrm{M}_{11} = \mathrm{I}_1 + \mathrm{I}_2 + \mathrm{m}_2\mathrm{L}^2$ and it depends on the inertia of the links, and consequently on density of the material.

F. MATLAB Energy Simulation

MATLAB was used in the implementation of the Lagrangian model. Trapezoidal angular velocity profile was ordered within a 2 s motion cycle. Each material arrangement had cyclic mechanical energy calculated as E = $\int \tau \, \dot{q} \, dt$. The MATLAB script ENERGY_SIMULATION was used to work through the two configurations one after another and provided the scalar energy values and a bar chart to compare these numbers directly.

3. RESULTS

A. Joint Torque Maximum Joint 1 torque was also 0.00643 Nm on CFRP arm versus 0.01085 Nm on the aluminium arm − 40.79 less. The two torque curves have the same temporal shape in the 2 s cycle - this confirms that the difference is caused by density, and not by kinematics.

B. Energy Consumption

Total mechanical energy per cycle was 0.1382 J (aluminium) and 0.0818 J (CFRP), a saving of 0.0564 J (40.78%). Table IV summarises all results against the analytical predictions.

Table 4
Simulation results vs analytical predictions

Metric	Analytical	Simulation
Al peak torque (Nm)	0.01085	0.01085
CFRP peak torque (Nm)	0.00642	0.00643
Torque reduction (%)	40.74	40.79
Al energy / cycle (J)	0.1382	0.1382
CFRP energy / cycle (J)	0.0818	0.0818
Energy reduction (%)	40.74	40.78

The results of the simulations are consistent with the analytical prediction differences within the range of 0.05 percentage points confirming that the 40.78% saving is solely due to the 40.74% saving in rotational inertia caused by the density ratio 2700 1600 = 1.6875. As CFRP elastic modulus was adjusted

to match the aluminium (70 GPa) real UD-CFRP laminates (100180 GPa longitudinal stiffness [23]) would provide the same or higher energy saving, therefore 40.78% is a floor.

4. DISCUSSION

The 40.78 percent energy savings is in line with independent publication reports: Kaitwanidvilai et al. [6] had found similar amounts of energy savings of composite substitution in an FEA-validated robot arm experiment; Pandey et al. [8] had found the same amounts of mass and structural performance savings of CFRP robotic arm components. Zhou et al. [10] established through subsystem energy attribution that the actuator force in contraction to link inertia is the main power consumption in motion-intensive operations, and the cornerstone to density-based substitution strategy used here. The outcome is extrapolated to other configurations such as the 2-DOF planar scenario examined. Since the percentage energy saved is only determined by the ratio of material density, the results are independent of the number of degrees of freedom, arm geometry and motion trajectory, so that the results can be directly applied to the more DOF industrial manipulators. Wierbica et al. [12] and Urrea [13] also verified that structural mass changes of this size add to other system-wide efficiency interventions, thus the 40.78 percent number is a bottom estimate of overall system improvement. The AutoCAD MATLAB workflow used in this case does not need finite element software and is therefore available as part of standard engineering tool sets and can be directly reproduced by users. Independent validation of the current assumptions made by simulation through physical systems Dominguez [2] and Tsakoumis et al. [11] both found that energy savings on this scale are repeatable in a physical system, which is not the first time the conclusions drawn by simulation have been validated by physical systems.

5. CONCLUSION

The present research shows that changing the links of a 2-DOF planar robotic arm with Aluminium 6061-T6 to UD-CFRP yielded a 40.79 and 40.78 percent reduction in the peak joint torque and the mechanical energy per motion cycle, respectively, with the results found to be within 0.05 percentage points of the density-ratio analytical prediction. This saving is accomplished by material substitution as opposed to the actuator, controller, or trajectory. Since CFRP stiffness was measured at a conservative of 70 Gpa, the 40.78 percent figure is a minimum of the physically achievable gain. The entire process - AutoCAD geometric modelling, MASSPROP mass extraction, analytical structural verification, Lagrangian dynamics, and MATLAB energy simulation --- does not need any specialist finite element software and can be repeated in the typical engineering setting. Further work must be carried out to cover complete 6-DOF systems, to add in actuator efficiency losses, to assess the ability of thermoplastic CFRP composites to be recycled and to assess the potential operational energy savings.

Declarations

DATA AVAILABILITY STATEMENT

This study did not use or generate any datasets. All results are derived from analytical modeling and simulations carried out using AutoCAD and MATLAB.

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Figures

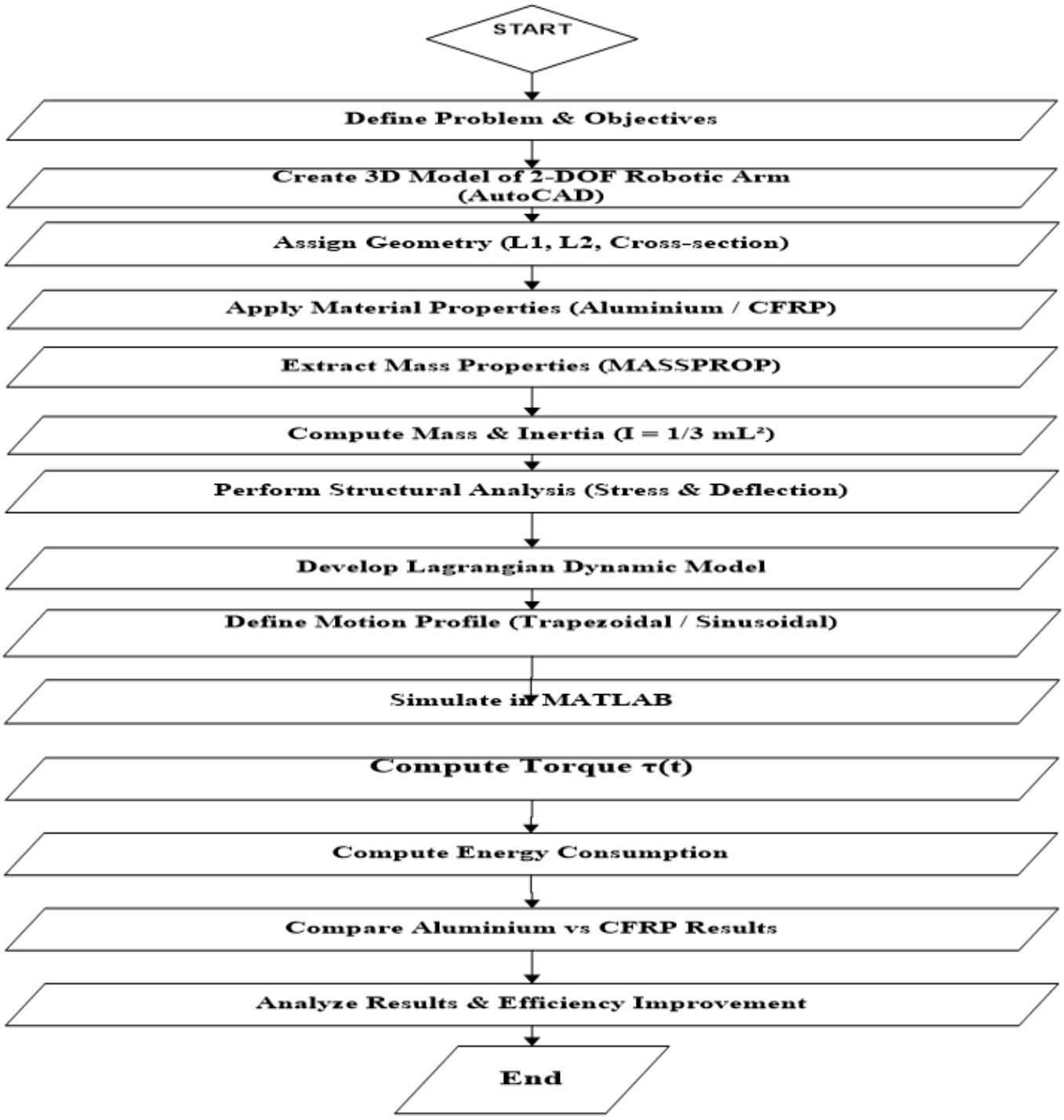


Figure 1

Simulation methodology flowchart: AutoCAD geometry modelling to MATLAB energy integration

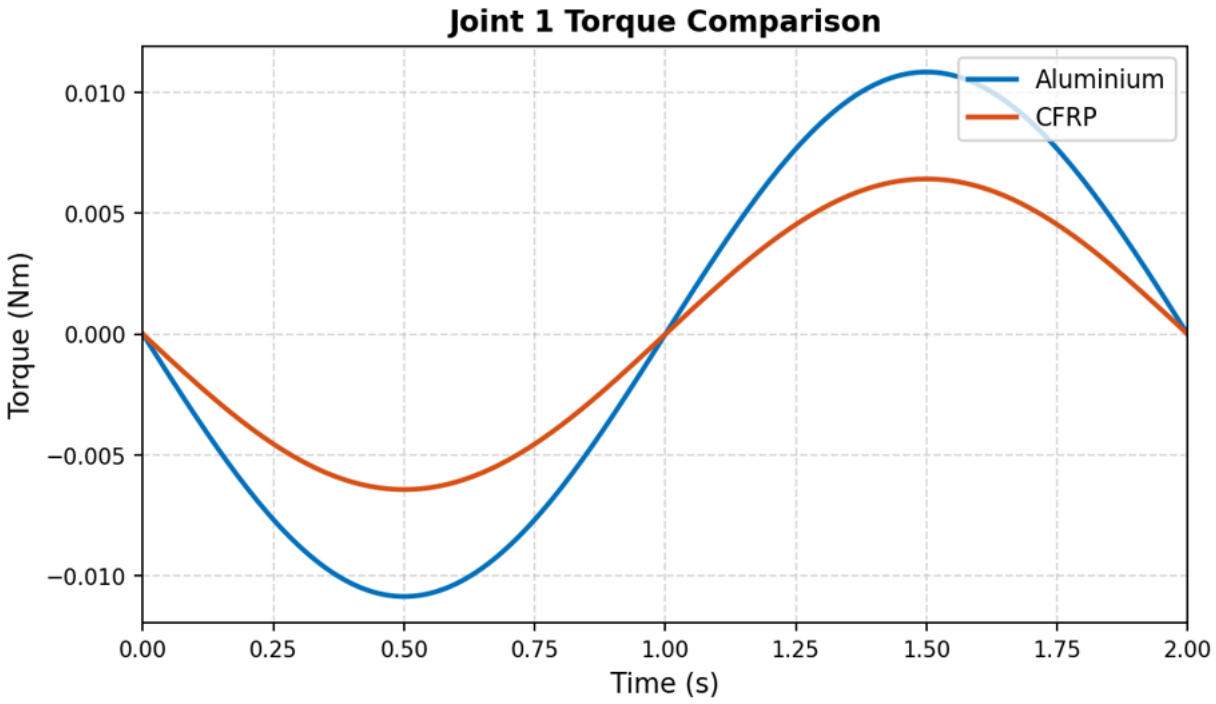


Figure 2

Joint 1 torque time history: Aluminium 6061-T6 vs CFRP over a 2 s motion cycle.

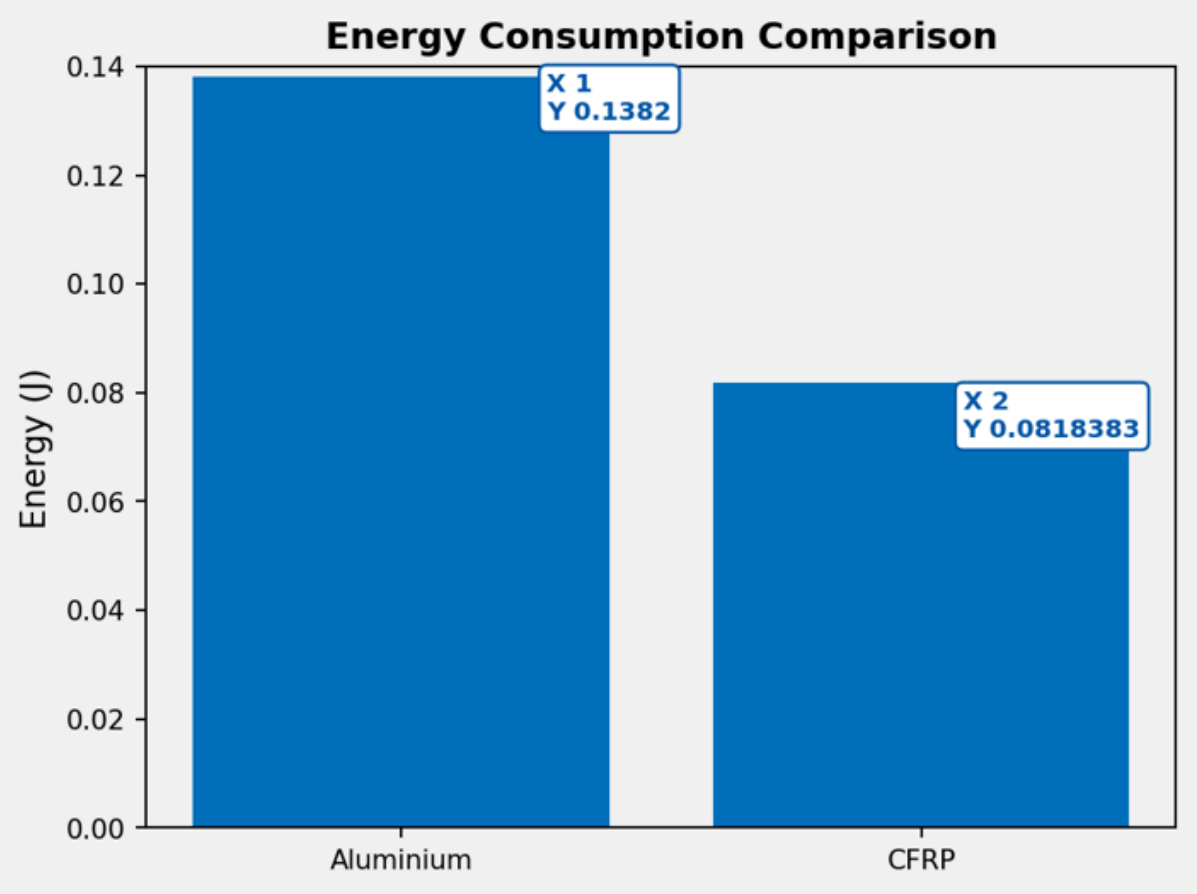


Figure 3

Energy consumption per cycle: Aluminium (0.1382 J) vs CFRP (0.0818 J).

Supplementary Files

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