Design Methodologies of the Hybrid Actuation Approach for Human-Friendly Robot

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Abstract—Safety is a critical characteristic for robots designed to operate in human environments. Presenting the analytical model of the hybrid actuation for human-friendly robot development, this paper has been proposed design methodologies to improve performance factors such as range of motion, payload, and acceleration while maintaining the safety factor of effective inertia. The optimized parameters with various design requirements have been provided with 1DOF and 2DOF applications. Comparison between current design parameters and the optimized parameters for a current platform shows the performance improvement. Several directions for future work into generalization and application for manipulator design and control are discussed.

I. INTRODUCTION

A. Background of Human-Friendly Robot

In these days, most commercial robots are deployed in restricted environment where close physical interaction between robot and human is strictly regulated. However, there is growing demand for human-friendly robots allowing operation in close proximity with humans. The hardest challenge in human-friendly robots supporting a variety of commercial uses is how to achieve the competing objectives of safety and performance. High performance robots employing powerful yet heavy motors with stiff and high-gear-ratio transmissions adversely increase reflected inertia and impact load in unexpected collisions between robot and human. Furthermore, since conventional robots display unexpectedly high impedance outside their bandwidth, they are not able to guarantee the safety with their active collision avoidance controller. On the other hand, safety robots designed with compliant drive trains significantly limit the robots' performance in terms of payload and control bandwidth. Previous efforts to increase the safety of robot arms while maintaining control performance have included relocating the actuators to the base and powering the joints with cables (PaCMMA)[11], [8] and employing a series elastic actuator (SEA) [10]. Zinn took both advantages of PaCMMA and SEA [19]. Other works have employed variable compliance [2], links with high-strength composite materials to minimize inertia [1], and compliant, energy-absorbing layers, and proximity sensors to detect impending collisions [9].

Most commercial robots exploit high stiffness to achieve high performance. They utilize high gear reduction ratio to

Fig. 1. Stanford Human Safety Robot (S2p)

compensate for the lack of the power of electrical motors. Unfortunately, this results in robots that have high effective inertia, since the inertia is proportional to the square of the gear reduction ratio. High stiffness and inertia can generate large impact force in a collision. While conventional robots are able to deal with external impact forces within their control bandwidth, they can display unexpectedly high impedance outside their bandwidth. Although safety can be achieved by the strict limitation of the power and velocity of high performance manipulators, as is done in medical devices, an innovative scheme must be developed to make general-purpose robots safe in human environments.

B. Hybrid Actuation Approach

Robots have traditionally relied on electromagnetic actuators, which offer excellent controllability but poor power-to-weight ratios compared to pneumatic muscles. Even more limiting is their inability to exert large sustained forces without high transmission ratios between the motor and the load. The high transmission ratios result in robot arms with high mechanical impedance, which are inherently less safe than their biological counterparts when unexpected contacts occur. To address these design issues, the Stanford Safety

Robot, $S2\rho$, employs hybrid actuation, combining powerful pneumatic actuators with small electrical actuators in a parallel configuration at each joint [13]. Key features embodied in the $S2\rho$ include: utilization of compact pressure regulators within the links; integration of valves, actuators and electronics around a sculpted, bone-like structural element; and replacement of heavy electrical actuators with compliant pneumatic muscles. However, the discovered limitations of the first-generation $S2\rho$ robotic arm are as follows: relatively slow pneumatic response caused by restricted air flow rates in the valves; limited strength-to-weight ratios for the bone structures; and a restricted joint motion and torque that result from limited contraction ratio of the artificial muscles.

The second-generation $S2\rho$ addresses three discovered limitations [14]. The macro pneumatic actuators are controlled by a new proportional valve system for fast response and smooth force control. The valves, along with the mini actuators and other components, are housed in a new thin-walled structure with Shape Deposition Manufacturing method [17]. This provides a combination of light weight and robustness. The new design incorporates multiple parallel pneumatic actuators at each joint to increase the range of motion and available torque without becoming bulky as shown in Fig. 1.

C. Design Optimization

The design should consider optimal design methodologies to improve the safety while maintaining the performance of the manipulator in three senses. First, air compressibility and viscous/coulomb friction of the pneumatic muscle cause force profiles to be highly nonlinear with respect to muscle length, which determines the joint configuration. In this sense, the appropriate determination of workspace and pulley radius guarantees optimal force profiles of an antagonistic pair of pneumatic muscles. Then, a wider range of motion and higher payload over all ranges can be achieved. Secondly, higher torque capacity of mini electrical motor contributes to higher performance in terms of payload and acceleration, but also results in higher effective inertia if high gear ratio and heavy-weight body are employed. Therefore, optimal mini actuator sizing should be conducted to achieve performance and safety. Finally, higher joint stiffness, which is obtained with higher average pressure for both muscles of an antagonistic pair [16], generally provides higher performance, but limits range of motion because the pneumatic muscles saturate faster. The optimal value of initial joint stiffness, i.e., average pressure of each muscle, must be determined considering wider range of motion without performance disruption.

The first design optimization is to determine kinematic design parameters such as payload, pulley radius, and range of motion. The second and third optimization is the combination of kinematic and dynamic optimal design. Previous efforts to develop kinematics optimal design includes workspace optimization with condition number, mass distribution, and manipulability [18]. Dynamic design optimization approaches include isotropic acceleration in low and high velocity [7],

Fig. 2. Hybrid Actuation. The macro is an antagonistic pair of pneumatic muscles, the mini is an electrical motor. The controller partitions the reference input torque between the low frequency actuation (macro actuation) and the high frequency actuation (mini actuation) based on the frequency. The torque applied on the joint will then be the linear combination of the macro and mini torque contributions.

an acceleration radius in continuous domain [6], and actuator selection based on dynamic criteria [15], [3].

This paper presents the actuation model and control strategy of the hybrid actuation in Section II. The Design methodologies and its problem formulation are provided in Section III, followed by applications in Section IV. Finally, the paper provides a conclusion and discussion of future work in Section V.

II. HYBRID ACTUATION MODEL

The $S2\rho$ robotic arm is controlled employing a pair of actuators, connected in parallel. The controller partitions the reference input torque between the low frequency actuation (macro actuation) and the high frequency actuation (mini actuation) based on the frequency. The torque applied on the joint will then be the linear combination of the macro and mini torque contributions, as shown in Fig. 2. For low frequency actuation, low impedance output is achieved by using the light pneumatic muscles. For high frequency actuation, low impedance is achieved by using a small low-inertia motor connected to the manipulator through a low-friction, low-reduction cable transmission. This results in reducing the weight of the moving arm drastically, while

Fig. 3. Macro Actuation Scheme, which consists of regulator and muscles. $P_1(P_2)$, $U_1(U_2)$, $F_1(F_2)$ and P_s denote regulated muscle pressures, muscle forces, command signal and supply pressure, respectively [12].

Fig. 4. Macro Torque Control with Adaptive Force Control. The block, Force Control, represents an individual muscle adaptive force controller. The compensator gain of macro force control is adapted with respect to the configuration. R and L denote the radius of the pulley and the length of muscle, respectively.

the on-joint mini actuator increases the control bandwidth and fast dynamics.

The macro actuation consists of antagonistic pair of pneumatic muscles and pressure regulator as shown in Fig. 3. The torque control of the macro actuation is based on the differential combination of pneumatic muscle force feedback control as shown in Fig. 4. The force feedback, closing the control loop around the pneumatic muscle through load cell, compensates for the pneumatic muscle force/displacement hysteresis phenomenon while also increasing the actuation bandwidth [12]. Given two forces, one from each muscle, the torque τ_M applied to each joint is

$$\tau_M = R(F_1 - F_2) = R\Delta F \quad (1)$$

where F_1 and F_2 are the forces generated by the pneumatic muscles and R is radius of the pulley. When the desired torque, τ_d , is to be produced at the joint, the necessary force difference ΔF_d , is symmetrically distributed between the two antagonistic muscles. Then a pressure regulator with proportional valves adjusts the flow direction and rate in order to control the force based on the load cell measurement. Mini actuation with an open-loop torque controller compensates for slow dynamics of the pneumatic muscle allowing the hybrid actuation to achieve higher frequency control bandwidth.

III. DESIGN METHODOLOGIES

A. Pulley Radius

The testbed of the hybrid actuation does not employ the analytical model for the force controller since force feedback with load cell measurement further reduces the non-linear effect in pneumatic muscles [14]. However, the general analytical model is essential to determine the design parameters before constructing a testbed. C.P. Chou et al. developed the analytical static model of the pneumatic muscle by

$$F = \frac{Pb^2}{4\pi n} \left(\frac{3L^2}{b^2} - 1 \right) \quad (2)$$

where, F , P , and L are force, pressure, and length of the muscle, respectively. The terms, b and n , are muscle constants [4].

Fig. 5. Muscle Force Profile with different radius of pulley at pressure of 40psi. It is not necessary for larger pulley radius to provide higher payload over all ranges, because the muscle force rapidly decrease as the muscle length decreases faster than that with smaller pulley.

However, the model predicts a higher force output than what was measured. In order to develop a simple yet adequate model for valid design optimization, an effectiveness term is introduced [5]. The dynamic model with effectiveness term is defined as

$$F = \begin{cases} \frac{Pb^2}{4\pi n} \left(\frac{3L^2}{b^2} - 1 \right) Eff(P) + Cv \pm Qk & \text{if } L > L_{min} \\ 0 & \text{if } L \leq L_{min} \\ 0 & \text{if } L \geq L_{max} \end{cases} \quad (3)$$

$$k = \frac{\frac{Pb^2}{4\pi n} \left(\frac{3L^2}{b^2} - 1 \right) Eff(P) - F_{min}}{L - L_{min}} \quad (4)$$

where, C is the viscous damping coefficient, which is proportional to the velocity of muscles tip, v . k is linearized actuator stiffness, Q is coulomb damping coefficient, and F_{min} is force at L_{min} [5]. According to the system identification, the term Qk is small enough to be ignorable in our experimental setup. Typically, a larger pulley radius provides a wider range of motion yet smaller joint torque, i.e., smaller payload. Hence, one of the goals of the design methodologies is to determine the appropriate pulley radius increasing payload over all ranges while maintaining a wide range of motion. However, since muscle force is non-linear with respect to the muscle length and also depends on muscle pressure, payload and range of motion relationship is not trivial. It is not necessary for a larger pulley radius to provide higher payload over all ranges, because the muscle force rapidly decrease as the muscle length decreases faster than that with smaller pulley. As shown in Fig. 5, muscle force with smaller pulley radius become higher as the joint moves farther from origin.

Optimal radius of the pulley is able to be determined in order to increase the range of motion while satisfying

payload requirement by following formulas.

$$\begin{aligned} & \arg \max_R \| q_{upper} - q_{lower} \| \\ & s.t. \quad q_{upper} = \max(q) \\ & \quad \quad q_{lower} = \min(q) \\ & \quad \forall q \in \{q \mid (\Delta F_{max})R - (A\ddot{q} + b + g) \geq J^T F_{pdes}\} \end{aligned} \quad (5)$$

where, ΔF_{max} , A , b , g , and F_{pdes} are maximum differential force at q , kinetic energy matrix, centrifugal and coriolis forces, gravity forces, and desired payload, respectively. The solution of this optimization problem also provides optimal workspace, q_{upper} and q_{lower} .

B. Actuator Sizing

Macro actuation with pneumatic muscles has slower dynamics than that of mini actuation with electrical motor. Thus hybrid actuation, especially in transient condition, requires overwork of mini actuator, which often causes saturation of mini actuator. This means the transient response of hybrid actuation strongly depends on the torque capacity of mini actuator. However, higher torque capacity is obtained at the cost of higher effective mass/inertia, from which the safety of robot suffers. Therefore, another goal of these design methodologies is to determine the appropriate mini actuator size to provide adequate performance without sacrificing the safety, i.e., low effective mass/inertia. The optimization formulas are given by

$$\begin{aligned} & \arg \min_{I_m} I_{eff} \\ & s.t. \quad I_{eff} = I_L + N^2 I_m \\ & \quad \ddot{q} = \frac{\tau_M - b(q, \dot{q}) - g(q) + N\tau_m}{I_{eff}} \geq \ddot{q}_{des} \\ & \quad \forall (q, \dot{q}) \in Q \end{aligned} \quad (6)$$

where, I_m , I_{eff} , and I_L represent motor inertia, effective inertia, link inertia. N , τ_M , τ_m , and $\ddot{q}_{des}$ indicate gear ratio, macro actuation torque, mini actuation torque, and desired acceleration. An entire operating region, Q , is the feasible subset of the manipulator state space, $(q, \dot{q})$. In practice, the operating region is determined by workspace with appropriate pulley size, and velocity limits due to actuator characteristic and task specifications.

Unfortunately, there exist no general equation to show this relationship between τ_m and I_m because the motor torque is complicated function of electronics as well as mechanics, which are different from manufacturer to manufacturer. In order to solve Formulas 6, we established estimated equation from inertia to torque using data sheet of eight samples of Maxon motors (RE series) and gearheads (GP series), which are best known for low inertia and high power-to-weight ratio. The gearheads are chosen among one-stage-gearhead for the minimum gear inertia.

As shown in Fig. 6, the torque of motor almost proportionally increases to the inertia of motor. With a linear fitting

Fig. 6. Torque vs. Inertia of Maxon motors. Estimated equation from inertia to torque using data sheet of eight samples of Maxon Motors (RE series), which are best known for low inertia and high power-to-weight ratio.

curve, Formulas 7 are rewritten as

$$\begin{aligned} & \arg \min_{\tau_m} I_{eff} \\ & s.t. \quad I_{eff} = I_L + N^2 I_m \\ & \quad I_m = 0.00028\tau_m - 3 \times 10^{-6} \\ & \quad \ddot{q} = \frac{\tau_M - b(q, \dot{q}) - g(q) + N\tau_m}{I_{eff}} \geq \ddot{q}_{des} \\ & \quad \forall \dot{q} \in \{\dot{q} \mid -180^\circ \leq \dot{q} \leq 180^\circ\} \\ & \quad \forall q \in \{q \mid q_{lower} \leq q \leq q_{upper}\} \end{aligned} \quad (7)$$

IV. APPLICATION

A. Pulley Radius and Range of motion

In order to verify the design methodologies for hybrid actuation of human-friendly robot, a simple one-degree-of-freedom robotic link (Fig. 7) is considered as

$$(I_L + N^2 I_m) \ddot{q} = (F_1 - F_2)R - C\dot{q} - Mg d \cos(q) + N\tau_m \quad (8)$$

$$F_i = \frac{Pb^2}{4\pi n} \left(\frac{3L^2}{b^2} - 1 \right) \quad i = 1, 2 \quad (9)$$

where, $I_L = 0.005 \text{ kgm}^2$, $N = 2$, $M = 0.356 \text{ kg}$, $d = 0.0815 \text{ m}$, $b = 0.1645$, and $n = 1.5$. C represents pneumatic muscle friction model experimentally identified as $C = \frac{20}{20 + \dot{q}}$, which is similar to the Hill model in Tondur's research

Fig. 7. 1DOF model. Motor torque, $N \times \tau_m$ is applied to the joint in parallel with the torque by an antagonistic pair of pneumatic muscles.

[?]. Using the Formulas 5 in Sec. III.A, the range of motion with respect to the joint position, q , and pulley radius, R , is shown in Fig. 8. If we choose the desired payload, P_{des} , of $20N$, then the optimal pulley radius $R = 0.016m$ while providing the range of motion of 94° as shown in Fig. 9. The corresponding workspace is $q_{min} = -80^\circ$ to $q_{max} = 14^\circ$.

Fig. 8. Pulley Radius vs. Payload vs. Range of Motion

Fig. 9. Pulley Radius vs. Range of Motion at a give desired payload of $20N$. Pulley radius of $0.016m$ provides range of motion of 94° .

B. Actuator Sizing

Considering the result of range of motion in the previous section and the task nature of human-friendly robot, the operating region, Q is defined as

$$\forall (q, \dot{q}) \in Q = \{(q, \dot{q}) \mid -60^\circ \leq \dot{q} \leq 60^\circ, q_{lower} \leq q \leq q_{upper}\} \quad (10)$$

Then, the system dynamic model, (8) and (9), are substituted into Formulas 6 in Sec. III to choose appropriate actuator, which satisfies the desired uniform acceleration while minimizing the effective inertia. However, since the

effective inertia of mini motor is much smaller than that of link, even the largest motor, i.e., largest motor inertia, always provides best performance without increasing the total effective inertia significantly. It is because the motor is mounted in the previous link, and the motor mass in 1DOF system is not included in the effective inertia model. To take the motor mass into account, we consider the simple 2DOF system, where, $I_{L1} = 0.015kgm^2$, $M_1 = 0.841kg$, $d_1 = 0.143m$, $I_{L2} = 0.005kgm^2$, $M_2 = 0.356kg$, and $d_2 = 0.0815m$. In order to simply analyze the emphasized joint, i.e., the second joint, we assume the first joint employs maximum torque motor within motor torque domain and initial position of the first joint is 20° . Another assumption is that while gravity is compensated by pneumatic muscles, the mini actuator deals with joint acceleration and overcoming friction of pneumatic muscles. Fig. 10 shows the minimum required torque capacity of the mini actuator to obtain a desired acceleration of $1.5m/sec^2$ in the x direction over an entire feasible joint angle and joint velocity set, Q . Since the acceleration requirement should be satisfied over all ranges, the optimal required motor torque capacity is the maximum value in Fig. 10, $0.42Nm$ at $(-18^\circ, 60^\circ/sec^2)$. In practice, the motor domain is a discrete continuous domain, hence a possible choice is Maxon RE30 with 5.8:1 gearhead GP32A or RE26 with 14:1 gearhead GP26B.

Fig. 10. Velocity vs. Position vs. Minimum Required Torque Capacity. Simulation is performed over an entire feasible joint angle and joint velocity set, Q , to obtain a desired acceleration of $1.5m/sec^2$ in the x direction. Since the acceleration requirement should be satisfied over all ranges, the optimal required motor torque capacity is the maximum value in this figure, $0.42Nm$ at $(-18^\circ, 60^\circ/sec^2)$.

C. Comparison with a current platform

Table I and II show the performance improvement with pulley radius optimization. The two optimization uses a desired payload and a workspace as an input, respectively. Table III shows decrease in actuator inertia with actuator optimization. The trade-off between higher-ratio gearhead with a smaller motor and lower-ratio gearhead with a larger motor will be discussed in the following section.

	Current Design	Optimized Design
Pulley Radius	0.020m	0.016m
Range of motion	88°	94°
Workspace	(-61°,27°)	(-80°,14°)

TABLE I. PULLEY DESIGN OPTIMIZATION AT A GIVEN PAYLOAD OF 20N

	Current Design	Optimized Design
Pulley Radius	0.020m	0.013m
Payload	6.1931N	9.5080N

TABLE II. PULLEY DESIGN OPTIMIZATION AT A GIVEN WORKSPACE OF (-60°,60°)

	Current Design	Optimized Design
Motor	RE26	RE30
Gearhead	14:1(Two stages)	5:8(One stage)
Actuator Inertia	$8.700 \times 10^{-4} \text{kgm}^2$	$4.808 \times 10^{-4} \text{kgm}^2$

TABLE III. ACTUATOR SIZING OPTIMIZATION AT A GIVEN ACCELERATION OF 1.5m/sec^2 .

V. CONCLUSION AND DISCUSSION

The concept of optimal design methodologies for hybrid actuation of human-friendly robot is presented with static and dynamic models of hybrid actuation. Once valid static and dynamic models of hybrid actuation system are derived based on the analytical models of pneumatic muscle, the optimal pulley radius for macro actuation, i.e., antagonistic pair of pneumatic muscles, is able to be determined to the extent that what workspace meets payload requirement without sacrificing the range of motion. Furthermore, it is feasible to select minimum/optimal mini actuator torque capacity to satisfy acceleration requirement without impairing robot safety.

However, these methodologies should be followed by a more accurate pneumatic muscle model, especially a friction model. The friction of joint transmission should be validated in a proper experimental setup. The methodologies will be generalized in order to be applied to the case of a higher-degree-of-freedom robot. Although the actuator of the current platform employs one of the optimized motor selections according to Sec. IV.B, higher gear ratio with two-stage-gearbox should be avoided in order to achieve better open loop control of the mini actuator. Meanwhile, the higher gear ratio is able to further reduce motor size to satisfy a desired acceleration, and thus decrease the effective mass. In the future work, this trade-off between motor size and gear ratio will be investigated. In addition, the pulley radius optimization will consider the variation of initial tension of pneumatic muscles, and actuator selection will take the frequency analysis into account for better control. The analysis of optimal stiffness will be conducted in order to reduce the interference between macro and mini actuation.

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