Control design for pick-and-place task using robot with intrinsic compliance - QB robot

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***Abstract*—Safe human-robot interaction is one of key issues in future service robotics. Numerous researchers have already invested a lot of effort to design passively compliant robots and to investigate active compliance through control algorithms. Due to sophisticated technology, hardware platforms which enable work with passive robots are mainly not affordable to researchers worldwide. In order to bridge this gap, QB Robotics designed low cost and open source hardware platform which is presented and used in this paper. The subject of the work was 4 DoF-s compliant manipulator, programmed to execute a pick-and-place task. We demonstrate control strategy which exploits variable stiffness of the robot actuators using antagonistic nonlinear springs. Control is based on pure position measurements, without force/torque sensors necessary for advanced control techniques. Developed control algorithm is successfully tested on the experimental setup.**

***Index Terms* — Antagonistic Joint, Soft Robot, QB robot, Position/Stiffness Planning and Control.**

I. Introduction: Control of Antagonistic Robot Joints

Next generation of robots are expected to work together with humans on production lines, as well as to cooperate and collaborate with humans in house and service works. Generally speaking, robots are anticipated to have important and immediate roles in everyday human lives. Therefore, conventional stiff drives are inapplicable and overcome due to their high inertia and inability to react instantly to collision with surroundings [1]. This fact leads us to novel robotic actuators with intrinsic compliance.

Detailed review on compliant actuators design was presented in [2]. Novel complaint actuators have been built to exploit passive compliance with emphasis on safe human-robot interaction and with increased energy efficiency due to proper placement of elastic elements. Basic design principle of compliant actuation is a combination of an elastic element of fixed compliance in serial configuration with a conventional electric drive which controls equilibrium actuator position [3]. Another approach to complaint actuator design is based on variation of physical stiffness due to change in the actuator structure - structure-controlled stiffness [4]. Similar approach is used in MACCEPA actuator designed at Vrije University [5] with only difference that structural change controls preload (spring pretension). The most relevant research on complaint actuators with its final aim to enable inherently safe human-robot interaction and therefore brings complaint robots as co-workers in real world applications has been conducted in European project such as Viactors [6], Stiff [7], and finally Saphari [8]. An actual review on variable stiffness actuators (VSA) is published by Vanderborght et al. in [9].

However, we focus on antagonistic actuator configurations whose design relies on biological principles of antagonistic muscles and their co-contraction and reciprocal activation to achieve both required position and compliance. Stated bio-inspired principles were firstly copied to technical realization by Magliore et al. in [10]. Afterwards, several technical realizations of an antagonistic setup appeared, using both electrical and pneumatic drives [11-14].

The paper is organized as follows. After a brief review on robotic joints exploiting compliant actuation and antagonistic principles in Section I, Section II gives insight in a novel variable stiffness actuator designed by QB robotics. Section III elaborates the concept of variable stiffness actuation on a pick-and-place case study. Section IV highlights experimental results which lead to final remarks and conclusions in the last Section.

II. Setup Overview - QBMove Maker pro and QB Robotics as Open Source Platform for Soft Robots

This section presents variable stiffness actuator with bidirectional springs in antagonistic configuration - qbmove maker pro [15]. Although very simple in design, the series of qbmove actuators moves the whole generation of compliant actuators to a new level - it is low cost, affordable and built on fully open-source principle. All mechanical and electrical drawings, build instructions, and manuals are available, so one can chose to built its own actuator or purchase one and save their time.

The inventor of QB move actuators is Italian company QB robotics, a spin-off of the University of Pisa and Italian Institute of Technology located in Genoa. The core activity of QB robotics is development and production of novel actuators and robotics subsystems in general, following the increasing trend in robotics – soft robotics [16-18]. QB robotics was established to build and promote robotic actuators which can move safely, smoothly, and efficiently, exploiting natural

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principles of motion control. In the other words, they aim to follow patterns and principles originated in skeleton/muscular systems of mammals. Therefore, beside safe human robot interaction, the goal is to exploit intrinsic elasticity to achieve energy efficient motion, speed and robustness.

Each QB robot actuator, qbmove maker pro, can be controlled by setting equilibrium position and stiffness preset (initial stiffness in absence of external torque), while antagonistically coupled motors are positioned to provide desired characteristics. Each actuator has three available pieces of sensor information – joint position (x), agonist (q_1) and antagonist motor position (q_2).

Both nonlinear springs in the bidirectional antagonistic configuration can contribute to overall torque τ in either direction (Figure 1). Thus, the contribution of each of them depends on spring characteristics, motor position and joint position. The setup can be approximated by (1) - (3), where (1) and (2) stand for contribution of each motor, while (3) sums its contribution to represent overall torque of the actuator.

$$\tau_1 = k_1 sinh(a_1(x - q_1)) \tag{1}$$

$$\tau_2 = k_2 sinh(a_2(x - q_2)) \tag{2}$$

$$\tau = \tau_1 + \tau_2 \tag{3}$$

Estimated spring parameters are: $k_1 = 0.0227\, Nm$, $k_2 = 0.0216\, Nm$, $a_1 = 6.7328 \frac{1}{rad}$, and $a_2 = 6.9602 \frac{1}{rad}$.

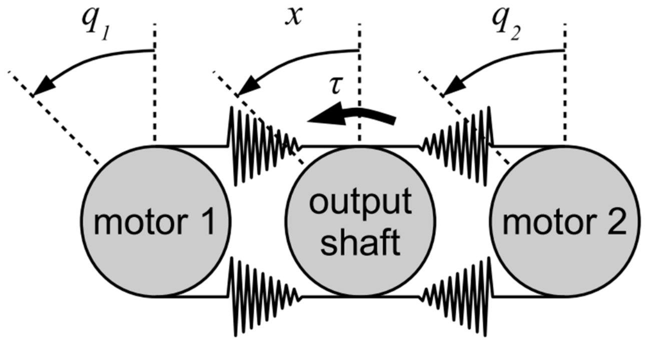

Fig. 1. Antagonistic actuator with bidirectional springs - configuration employed in QB move actuators

Figure 2 displays schematic drawing of qbmove maker pro actuator using bidirectional springs in antagonistic configuration. The configuration ensures output torque that satisfies approximations (1)-(3). However, note that bidirectional antagonistic configuration is not faithful copy of mammals antagonistic musculoskeletal systems [19], since muscles can only pull and not push, but rather its engineering approximation. In this way, controllability issue is prevented.

Realization of schematic drawing is depicted in Figure 3. The actuator can deliver continuous output power $P_{NOM} = 4.8\, W$ (nominal torque $\tau_{NOM} = 1.2\, Nm$ and nominal angular velocity $\omega_{NOM} = 4\, rad/s$). In order to be widely used and employed, qbmove maker pro beside low cost offers common electrical interfaces – USB type B and RS485. The actuator covers full circle range of $\pm 180\, deg$.

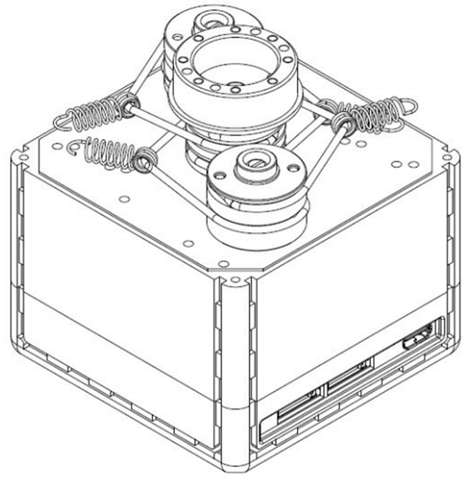

Fig. 2. Schematic of qbmove maker pro actuator using bidirectional antagonistic springs

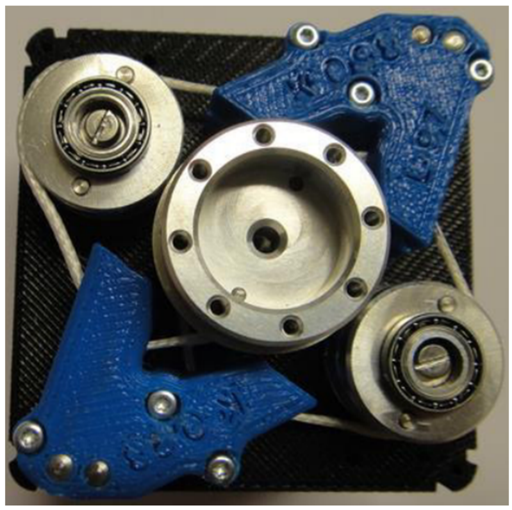

Fig. 3. Physical realization of qbmove maker pro actuator using bidirectional antagonistic springs

In accordance to the design of the actuator, both motors can equally contributes to joint position (4), and overall joint stiffness preset by co-contraction (5). Each QB move actuator has the interface which enables direct setting of equilibrium joint position or stiffness preset. The desired motor positions are afterwards set through direct analytical relations (4) and (5) between motor positions and two input values.

$$x_{eq} = \frac{q_1 + q_2}{2} \tag{4}$$

$$\sigma = a_1 k_1 cosh\big(a_1(x - q_1)\big) + a_2 k_2 cosh(a_2(x - q_2)) \tag{5}$$

The realization of this variable stiffness actuator, based on the antagonistic principle, can deliver nominal torque of $\tau_{NOM} = 1.2$ Nm while its stiffness ranges from $\sigma_{MIN} =$

0.5 Nm/rad to $\sigma_{MAX} = 12\ Nm/rad$. As it is expected, stiffness deviates more from its preset value for lower stiffness preset intensity than in a case when an initial co-contraction makes the actuator stiff (Figure 4). Figure 4 and Figure 5 demonstrate nonlinear stiffness characteristics required for variable stiffness actuators [10]. Due to its visco-elastic properties, torque-deflection characteristic shows hysteresis nature (Figure 5). According to Figure 5, maximal deflection from equilibrium position ranges from $9\ deg$ (maximal stiffness preset – in red color) to $36\ deg$ (for minimal stiffness preset – in blue color).

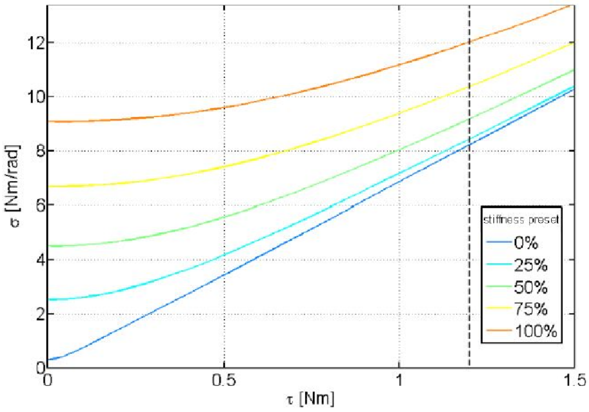

Fig. 4. Torque-stiffness characteristics of qbmove maker pro actuator using bidirectional antagonistic springs

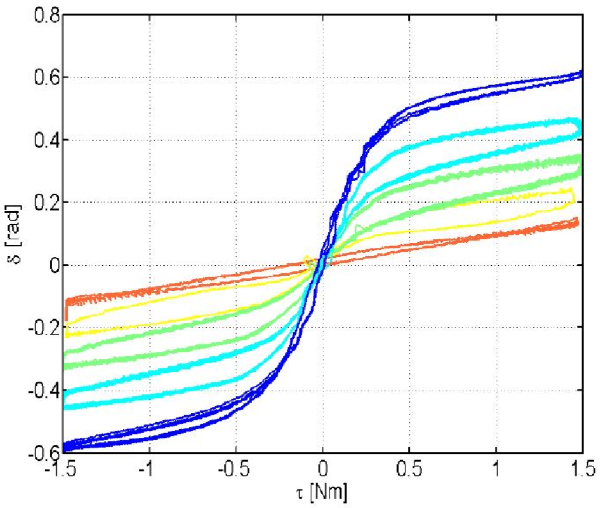

Fig. 5. Torque-deflection characteristics of qbmove maker pro actuator using bidirectional antagonistic springs

Conventional rigid drives are chosen so that the range of torque and velocity fits within working area (continuous work region below torque-speed characteristic). However, for drives with variable stiffness actuation this is not sufficient. Namely, not all combinations of torque-velocity-stiffness values are possible. The cross-analysis of actuator characteristics (torque, stiffness, and velocity), lead to achievable triplets presented in 3D graph (Figure 6). Detailed insight from users' stand point regarding variable stiffness actuators is presented in [20].

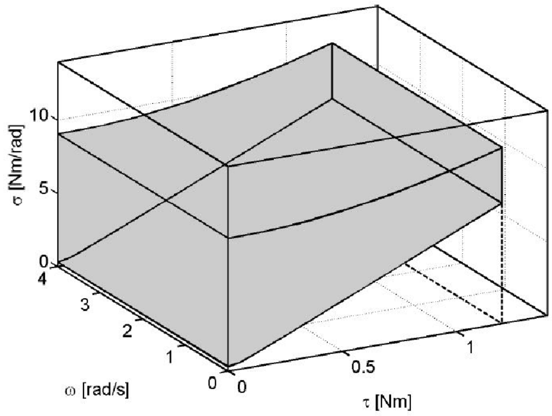

Fig. 6. Torque-velocity-stiffness workspace of qbmove maker pro actuator using bidirectional antagonistic springs

Authors of the QB move actuators have already presented some possible applications of the hardware in contact and interaction tasks [21, 22]. Future improvement of the actuators should provide additional sensor information so advanced control techniques could be applied. To this end, one of the challenges that should be tackled is stiffness estimation [23].

III. Case Study: Control Design for Pick-and-Place Task using Robot with Intrinsic Compliance

The presented case study of the pick-and-place task using the soft robot manipulator (Figure 7) is a result of winning team from Winter School on Variable Stiffness Actuators, organized by National Machine Motion Initiative (NMMI) [24] and Safe and Autonomous Physical Human-Aware Robot Interaction (SAPHARI) project consortium [8]. The task was to pick an object from its initial stand and place it to its final destination - the final stand. Note that the task was planar and it contained peg-in-hole task while delivering the object to its final stand. The goal was to ensure robust control which would successfully deal with slight dislocation of the initial and final destination.

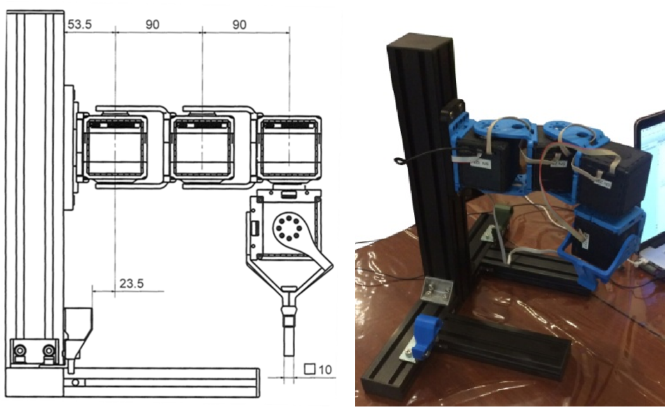

Fig. 7. Experimental setup - 4 DoF-s compliant robot driven by QB robotics variable stiffness actuators - qbmove maker pro; (left) schematic drawing (right) physical realization of the experimental setup.

To this end, several aspects were considered: trajectory planning, planning stiffness preset, smoothing the trajectory by interpolation, and finally fine PID tuning for each joint to ensure desired trajectory tracking. Starting from robot initial position, the task was picking the object, carrying on the object towards the final stand, placing it in the hole (final object destination) and returning to the initial robot position. The robot has 3 controllable DoF-s to enable full positioning and orientation in 2D plane (XY position & orientation). The 4th DoF was gripper as an end-effector.

To ensure robustness to dislocation of the initial or final object stand, the trajectory planning while picking and placing the object was of key importance. In order to pick the object, robot was guided to slide along the axis where the initial stand with the object was expected, while at the same time orientation of the gripper should remain constant. Beside the trajectory, during this contact planning the compliance was equally important. During the grasping, compliance was lowered to prevent high interaction forces due to uncertain position of the initial stand along the line where robot slides expecting to collide with the object and picking it. Immediately after the picking was performed, the robot was instructed to move aside the object from the initial stand while keeping the same orientation of the gripper and moving it along the axis perpendicular to the one where it had been sliding in order to pick the object. At the same time, stiffness preset was still on law level to avoid high interaction forces if collision occurred. While carrying on the object towards its final destination the robot was instructed to stiffen in order to ensure better trajectory tracking. The most challenging assignment was placing the object to its final destination, since it was peg-in-hole problem. To that end, the gripper was initially positioned to axis parallel to the axis of the hole in the object final stand (its expected position). At the same time stiffness was set to the low level in the 3rd robot joint (the one responsible for the orientation of the gripper) while the first two joint preserve rather high stiffness preset value to ensure proper positioning. In this manner, robot end-effector was stiff enough to ensure desired position, but at the same time compliant enough to deal with dislocation of the hole, since the compliance in the orientation enables the object to slide into hole and avoid high collision forces. Finally, the robot was instructed to return in initial position which is its final position at the same time, avoiding the placed object and object final stand.

All the trajectories were recorded by manually moving the robot (Figure 8. Manual switch2 in reading position mode - desired equilibrium position is equal to the current position) through the key points while saving the joint positions. Therefore, the planning of the trajectory and stiffness was done to exploit variable stiffness actuators of the robot by setting stiffness preset to high values when the trajectory tracking was of key importance and setting the low stiffness preset values when the contact was expected.

After the key points were chosen linear interpolation for trajectory smoothing was performed [25]. This was of particular importance to ensure good trajectory tracking and avoid oscillations which could easily appear due to intrinsic elasticity of the system.

Finally, incremental discrete PID controller was tuned for each axis. Since qbmove maker pro actuator interface require the equilibrium position as an input, the joint position x is controlled by setting desired equilibrium position x_{eq} according to (6)-(8). x_{ref} stands for desired joint positions.

$$e = x_{ref} - x \tag{6}$$

$$K_{PID}(z) = P + I \cdot T_s \cdot \frac{1}{z-1} + D \cdot \frac{N}{1+N \cdot T_s \frac{1}{z-1}} \tag{7}$$

$$x_{eq} = x + K_{PID}(z) \cdot e \tag{8}$$

The sampling time was set to $T_s = 5ms$. Gains of the PID controller (7) for each joint are displayed in Table I.

One can note that gripper is controlled using pure proportional controller. This was done by purpose to avoid integrator wind up since the firm grasp is accomplished by setting the reference joint position higher than $45deg$ which was position of the closed gripper. Thus prominent joint deviation ensured firm grasp, while avoiding wind up effect.

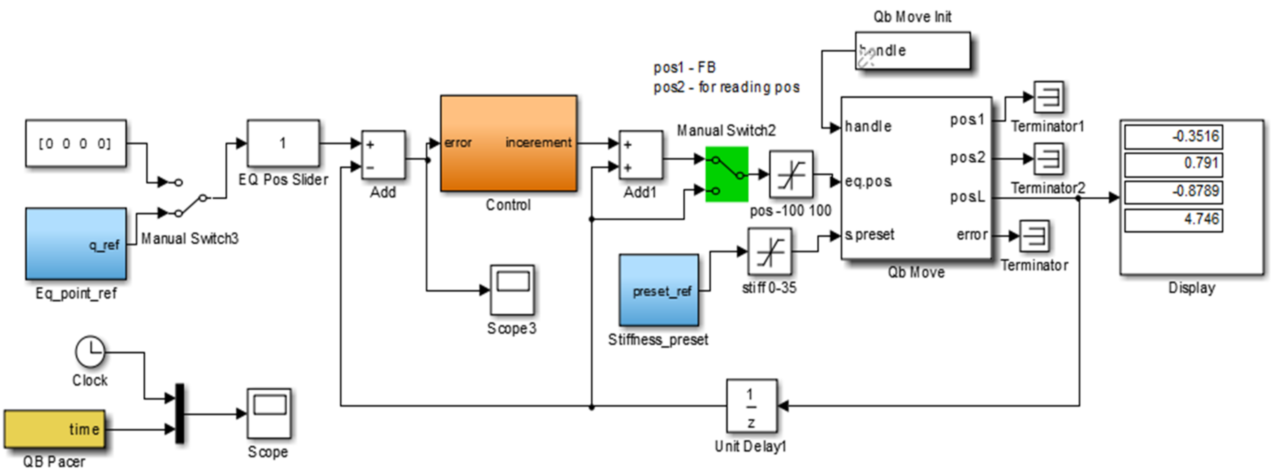

Fig. 8. Control design of the robot built from QB move maker pro actuators in pick-and-place task. *Qb Move* block is Simulink interface for real-time control of QB robotics actuators. Each joint is controlled in decupled way using discrete incremental PID controller (in orange). Trajectory and stiffness planning (in blue) is done to exploit compliant actuator characteristics and ensure robustness for the task.

TABLE I
PID CONTROLLER GAINS

Joint number	P	I	D	N
1 (1st XY position)	1.1	0.5	0.05	50
2 (2nd XY position)	1.1	0.5	0.05	50
3 (XY orientation)	0.9	0.35	0	x
4 (gripper)	0.9	0	0	x

IV. EXPERIMENTAL RESULTS

This section presents experimental results on the task which is described in details in the previous section. Figure 9. points out trajectory tracking in each of total four joints. Desired positions are given in solid lines while their actual values are depicted in dashed lines.

Although the robot was constructed using low-cost hardware components, presented results demonstrate satisfactory trajectory tracking. One can distinguish three phases: the first ($t < 4s$) and the third phase (t > 11s) the stiffness preset is set to low level and therefore trajectory tracking deviates more; the second phase ($4s < t < 11s$) is phase when stiffness preset is set to high level and therefore tracking error is low due to rigid-like robot behavior. The highest deviation is notable in the 4th joint (gripper), where the position is set higher than the position of the closed gripper ($45\ deg$). As explained in the previous section, this was the solution to achieve the firm grasp without winding the integrator control component. Here the role of compliance is also demonstrated since during the grasping ($4s \div 5s$) 4th joint deviated more to compensate for interaction force since the object was still in its initial stands and therefore contact force occurred.

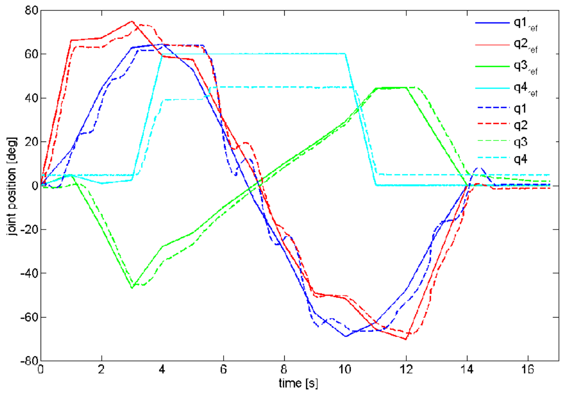

Fig. 9. Joint position tracking.

V. CONCLUSION

There is no doubt that robots are becoming common content of our human centered environment. Therefore, novel actuators with intrinsic elasticity, especially their design and control, are research scope of numbers of robotics research centers. However, experimental setups/robots on the topic are mostly expensive and unreachable for many. This paper presents the variable stiffness actuator with bidirectional antagonistic springs which confronts these prejudices. QB robotics offers low cost, affordable platform – QB move actuators which could move your soft robot.

The presented case study was the result of winning team from Winter School on Variable Stiffness Actuators. It contained control design for pick-and-place task involving peg-in-hole assignment while delivering the object to its final destination. In order to exploit manipulator compliance, the goal was to ensure robust control which would successfully deal with slight dislocation of the initial and final destination. The task was successfully solved by symbiosis of trajectory planning, stiffness preset planning, and control design for each axis driven by described compliant antagonistic actuator.

In order to contribute the final aim - to incorporate soft robots into our everyday environment, this work will be extended. Our future work will observe biological patterns of antagonistic muscular system and consider their application to the robot. We expect to exploit some natural motion to obtain safe, accurate and energy efficient solutions.

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Figures 1, 2, 4, 5 and 6 are extracted from the qbmove v0.1 (maker pro) datasheet, available at [26], distributed under the Creative Commons Attribution 4.0 International License [27].

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