Supplementary information

Here we include a discussion of issues that should prove informative to those readers less familiar with the basic design issues regarding manipulanda. We also include sufficient information for those interested in building their own units. Many electro-mechanical design requirements are contradictory and any design represents a trade-off between various desirable characteristics. No single aspect of design can be considered in isolation since the selection of any given part will influence the choice of others and affect the overall performance. Section S1 discusses design considerations, section S2 discusses actuation and section S3 discusses issues specifically related to the arm and handle.

S1 Design considerations

S1.1 End-point mass

One property that needs to be kept to a minimum is the effective end-point mass of the manipulandum. This is the equivalent mass at the handle that would yield the same moment of inertia as actually realized by the mechanism. Since moment of inertia about an axis is proportional to mass multiplied by the square of its distance from the axis, this has important design implications. Components with high mass may be acceptable if they are located very close to the axis of rotation. Therefore using a massive steel shaft for the principle axis of the manipulandum will not excessively contribute to the effective end-point mass. The inertia of the drive motors will also contribute. It is also worth noting that the use of pulleys to increase torque will increase the moment of inertial of the drive system, which scales with the square of the ratio of the mechanical advantage. In many industrial robots, actuators are often located on the arm joints themselves. This cannot be adopted in uncompensated manipulanda because it increases the effective end-point mass unacceptably.

S1.2 Stiffness

To ensure accurate correspondence between the end-point position and the measured angular positions at the motors, the intervening mechanical structure and its support must be as rigid as possible. High stiffness is also necessary to ensure the manipulanda has an acceptably high mechanical bandwidth. Specifically, this should be greater than the effective bandwidth of the human arm. High stiffness can be achieved by employing a sturdy construction for all non-moving parts and using materials with a high stiffness-to-mass ratio for all moving components. Therefore, the base plate and arm supporting structures should be made extremely rigid, whereas for all moving parts a compromise must be reached between stiffness and mass. This is particularly true for the arm mechanism. Consequently in our design the arms are largely built using carbon fibre composite tubes and the shafts are made from steel. All other parts of the manipulandum are constructed from 6082 aviation grade aluminium alloy, which offers a high strength-to-mass ratio and is easy to machine.

S1.3 Mechanical play, friction and viscosity

The lack of stiffness is not the only source of “give” in a mechanism. Mechanical play between components gives rise to a non-linear hysteresis effect known as “backlash” and can result in a sudden jump in position whenever drive direction is reversed. Backlash can arise from poor fitting shafts and bearings and thus care must be taken to use only high precision components to keep this to low levels. Typically, bearings will exhibit a very small amount of backlash. In a series transmission system, such as the vBOT arm, overall backlash at the handle will arise due to the summed contributions throughout the mechanism. There is consequently no benefit in any one source being reduced excessively without other sources also being reduced. To minimize friction, drive motors with high ratio gearboxes must also be avoided, as should other components such as industrial encoders that are hermetically sealed. Low friction bearings should be employed at the joints and they should also run with minimal levels of lubrication to minimize viscous resistance.

S1.4 Position measurement

Accurate measurement of the handle position is an essential aspect of manipulandum operation. Moreover, unless additional sensors are included, the position signal must be use to calculate velocity and acceleration. Handle position need not be measured directly but rather can be computed from measurements of angular position at the motor shafts using high resolution incremental encoders. Placing encoders at this location is preferable to placing them at the arm joints because they remain stationary, which again avoids adding unnecessary moving mass to the arm. This close coupling of the encoders to the motors also contributes to control stability.

S2 Actuation

S2.1 Output force

Ideally, the manipulandum should be able to apply force over a range that is compatible with the range of forces produced by the human arm. In addition, it needs to generate force whilst moving at typical hand speeds. However, there are practical limitations that arise in meeting these requirements. For example, a compromise must be made between the maximum force output and the intrinsic dynamics of the actuators. High output force manipulanda can also be dangerous, so there are safety reasons for limited the maximum force output.

S2.2 Type of actuator

The requirement for back-drivability and minimization of the intrinsic dynamics of the manipulandum precludes the use of actuators that are often used in many industrial robots, such as hydraulic cylinders and motors using worm or harmonic drives.

It is possible to use direct drive motors to power the arm and such designs exhibit low moving mass and low friction. However, suitable motors and their controllers are several times (e.g.. up to x5) more expensive than ones that require an additional mechanical advantage in their transmission. In contrast, we adopt a design using smaller motors and a timing pulley mechanism to achieve the necessary mechanical advantage. This gives us maximum end-point force of approximately 40 N, which is suitable for most motor learning paradigms. Steel reinforced timing pulleys offer a good solution since they are very stiff and also introduce virtually no backlash in the transmission system. They do exhibit some friction, but this is still quite low. The moment of inertial of such a transmission system can also be kept low if spoked pulleys are employed. Such a drive mechanism is also rigid since the arm and main shaft can be supported independently of the motors.

S2.3 Motor and controller issues

Many aspects of motor performance depend upon the combination of a motor and its control electronics (a servo amplifier and its power supply). Manufactures often supply amplifiers matched to their motors and this greatly facilitates the construction of electromechanical equipment such as robots. In a manipulandum it is important that the combination of motors and control electronics result in smooth vibration-free movement of the handle. Human subjects are very sensitive to vibration which thus must be kept to a minimum to prevent the generation of unwanted cues during experiments. Consequently the motor drive mechanism should have low mechanical noise and should not exhibit the torque fluctuations referred to as “cogging”. It should be noted that some digital controllers do not meet this requirement and generate noticeable torque fluctuations when generating a static torque. Linear amplifiers can lead to smoother control and generate less electrical interference than switching ones. They also result in less motor heating for the same mean output torque (Murat Cenk Çavuşoğlu 2002). However, such units are much more costly and dissipate a large amount of heat themselves.

S2.4 Choice of motors

Motor selection depends on several factors. The maximum static torque that can be generated by a motor/controller combination is determined by the motor’s torque constant and the maximum current rating of the motor and/or controller. The maximum torque a motor/controller combination can generate often falls as the rotational speed of the motor rises. In the stall condition, to pass the required current through the motor to generate a desired output torque requires the application of a voltage to overcome the electrical resistance of the motor windings. This voltage will be quite a low value and usually much less than the maximum output voltage available from the control amplifier. However, as a motor rotates, it generates a back electromotive force (EMF). If the difference between controller output voltage and this back EMF is less than that necessary to cause the required current to flow, the motor output torque will fall short of the desired value. This situation can often be avoided by running the controller at its maximum rated supply voltage.

The maximum continuous torque of a motor is often limited by the thermal characteristics of the motor, since passing current though a motor will cause heat dissipation in its winding, causing an increase in temperature. This must remain below a maximum value or the motor will burn out. The maximum intermittent torque for the same motor is usually substantially higher than this value, because it has the chance to cool down between activations. In fact, the maximum intermittent torque is often limited by the maximum output current capacity of the controller, and not the motor. It should also be noted that as the temperature of the motor rises, its torque constant may decline. Therefore, to maintain a linear current/force relationship is it also desirable to run motors cool and below their maximum ratings. Overheating can be avoided if the control software implements a simple temperature tracking algorithm that turns off the motors at a safe threshold.

There was also a legacy issue in the selection of motors, in that we wished to design a system that was compatible with other experimental equipment in our laboratory and this biased the choice of motors and controllers towards Maxon units (Maxon Motor AG, CH-6072 Sachseln).

S3 Arm and handle

S3.1 Arm

The arm is the most critical component in the entire design because it is the source of most of the effective end-point mass and compliance in the manipulandum. These undesirable properties also dramatically increase with its size. The stiffness of the arm decreases with length cubed, whereas the moment of inertia increases with length cubed. Therefore, the length of the arm and corresponding 2D workspace of the manipulandum should be large enough to accommodate the range of human arm movements, but no larger. Additionally, it is important that mass and friction are as isotropic as possible, because significant asymmetries would introduce a direction-dependent bias.

To ensure that the arm can be used free standing without extra end-point support it must withstand downward forces generated by the subject resting on it with at least the weight of their arm. Subjects have also been known to support their body weight on the handle which they use to lift themselves out of the rig. This requires that the arm be structurally strong in all directions and not just in the plane of movement. Round section carbon fibre composite tubes provide an ideal contender for such a design because they are currently one of the stiffest materials available for a given mass and are easy to produce. A more complex design using planar cross section links, such as employed by the ATR PFM manipulandum described in the main paper, would increase the stiffness-to-mass ratio in the plane of movement at the expense of decreased stiffness perpendicular to the plane. However, such sections are difficult to construct and also many times more costly. The use of carbon fibre achieves a low effective end-point mass at the handle whilst still achieving high stiffness.

To support bimanual paradigms, the arms should be designed so two vBOTs can be used side by side. This requires that the arm linkages on two adjacent robots do not protrude into each other’s workspace, so as to avoid collisions. This can be achieved if the arms can be reversed at the elbows in a mirror-image fashion, so that the two handles can occupy the central workspace without the arms colliding.

S3.2 Handle

Forces are most usually applied to the subject by a handle which they grasp with the hand. If required, a splint can be attached to the handle to support the arm. Since the handle is located at the distal end of the arm it must be light to avoid adding significant mass to the end-point. The handle should freely rotate with respect to the robotic arm. It should be comfortable to hold and have a high friction surface so that subjects can maintain a firm grip without slipping.

References

Murat Cenk Çavuşoğlu DF, Frank Tendick. A critical study of the mechanical and electrical properties of the PHANToM haptic interface and improvements for high-performance control, Presence. Teleoperators and Virtual Environments, 2002; v.11 n.6: p.555-68.