Towards a Test Battery to Benchmark Dexterous Performance in Teleoperated Systems

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Abstract. A high level of dexterity is becoming increasingly important for teleoperated inspection, maintenance and repair robots. A standard test to benchmark system dexterity can advance the design, quantify possible improvements, and increase the effectiveness of such systems. Because of the wide variety of tasks and application domains ranging from dismantling explosives from a safe distance to maintenance of deep sea oil rigs, we defined a library of basic, generic tasks and selected five tests that reflect these basic tasks and for which benchmark data already exist or are easy to gather: the Box & Block test, the Purdue Pegboard test, the Minnesota Manual Dexterity test, the ISO 9382 trajectory test (based on the ISO 9382:1998 standard) and the adapted version of the screwing subtest of the IROS 2017 service robots challenge.

Keywords: Haptic · Dexterity · Teleoperation · Test battery · Standards
Benchmarking

1 Introduction

Successful robot operation in for instance unpredictable environments relies on optimal integration of human (motor) intelligence, flexibility and creativity and robot precision, power and endurance. Therefore human (motor) intelligence will be needed for remotely operated robots in ever changing situations with unpredictable task constraints, perhaps for decades to come. With recent advances in technology, a high level of dexterity is becoming increasingly viable for teleoperated Inspection, Maintenance and Repair robots (IRM), the use case we employ in this paper. Currently, there is no standard test or instrument available to benchmark system dexterity, while such a benchmark is important to advance system design, quantify possible improvements (like adding certain feedback modalities), and increase the effective application of such systems. Our aim is to come to a simple and generic test set to benchmark dexterity of teleoperated systems. Our approach is to define a library of basic tasks and re-use or adopt existing tests (for instance from the rehabilitation domain) to benchmark task performance.

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1.1 Background

Traditionally, robots are used to perform tasks that are dull, dirty or dangerous (the 3 D's) for humans. Although the application of robots nowadays expands into many more fields (e.g. service-oriented or time-critical), the 3 D's, as they are known, remain key driving factors for many robotics systems. Especially the robots doing "dull" jobs have a high degree of autonomy, which is still increasing thanks to increased techno-logical capability. Autonomous robots can plan and to some degree adapt tasks in reaction to changing circumstances without human interference. Although the advances in autonomy are rapid, autonomous robots will not be a viable option in all ("dirty" or "dangerous") cases for the foreseeable future (SPARC 2017). Autonomous robots are often designed to perform a specific task, in a specific type of environment. If the tasks of a robotic system are diverse, the environments unpredictable and the stakes of successfully performing the task are high, autonomy will not be relied upon. This is the case in for example explosive ordnance disposal, and maintenance and disaster response on petrochemical sites. In these applications, robots will not be able to carry out all necessary tasks with sufficient reliability without human involvement.

The common solution in these use cases is teleoperation (Van Erp et al. 2006). In teleoperation the task is performed by an operator controlling the robot remotely, typically in a master-slave setup. Since the cognitive part of the task still remains with the human operator, a wider array of (unexpected) tasks can be performed – given sufficient sensory, movement and manipulation abilities of the robot. Teleoperated robots are often used for collecting data about the environment, in order to decide on further courses of action (i.e., *telesensing*). With increasingly advanced robots, manipulation of the environment becomes a possibility as well: *telemanipulation*. Telemanipulation can be used in order to reach certain areas (e.g. opening doors or bags), or to perform a critical part of the task (e.g. sampling a fluid, closing a valve, cutting a wire).

This paper concerns the manipulation of the direct environment of a robot (i.e. the telemanipulation part of teleoperation), with one or more robotic arms and end effectors. Using IRM as use case, we define a library of basic tasks (Sect. 2) and describe relevant dexterity tests in Sect. 3. Sections 4 and 5 present the selection criteria and the final test selection, respectively. In Sect. 6, we discuss the results and way forward.

1.2 Definitions of Dexterity

Dexterity is often considered as a mechanical property of the robot itself. Several authors propose different definitions (Ma and Dollar 2011). Bicchi (2000) and Li et al. (1989) stress the importance of being able to move an object to any arbitrary position and orientation within the workspace, while other authors limit dexterity to in-hand manipulation only (e.g. Bullock et al. 2013). What all definitions have in common though is: (a) that the robot has to be able to perform in-hand (or in-effector) manipulations using different ways of gripping, and (b) that the manipulator typically needs a redundant number of degrees of freedom. An example of an effector with a high level of dexterity is a hand-shaped gripper with four independently moveable 'fingers', allowing manipulation within the effector, while an example of an effector with a low level of dexterity would be a two-finger parallel gripper. The use of more than one effector appendage or arm, or combining several types of effectors will increase the level of dexterity.

We adopt the definition of Okamura et al. (2000): "Cooperation of multiple manipulators, or fingers, to grasp and manipulate objects,". For the purpose of this paper, we extend that definition to include the complete teleoperated system, including the robot, communication channel, human interface and human operator, not just the (isolated) end effector. For instance, adding haptic feedback does not change the dexterity of the end effector but may increase dexterous performance of the teleoperated system as a whole.

2 Library of Basic Tasks

Defining basic tasks is required since the number of possible movements is virtually infinite (Bullock et al. 2013) and the number of tests and evaluations is also very large, even for a single application domain. To be able to select the appropriate tests, we defined a library of basic tasks for our IRM use case. Additional libraries may be developed for other domains like surgery. Based on inspection, maintenance, and repair activities, a library of basic tasks was created. The basic tasks can be considered as basic building blocks and can also be combined to form more complex tasks. A basic task is a simple task that can be performed in a variety of contexts, goals, and restraints, but consist of the same movements when the context is removed. The basic tasks that were defined are: (a) screwing an object off another object; (b) screwing an object on another object; (c) placing a constrained object; (d) removing a constrained object; (e) placing a freely movable object; (f) removing a freely movable object; (g) following the external structure of an object; and (h) following a visual trajectory. All basic tasks are depicted in Fig. 1.

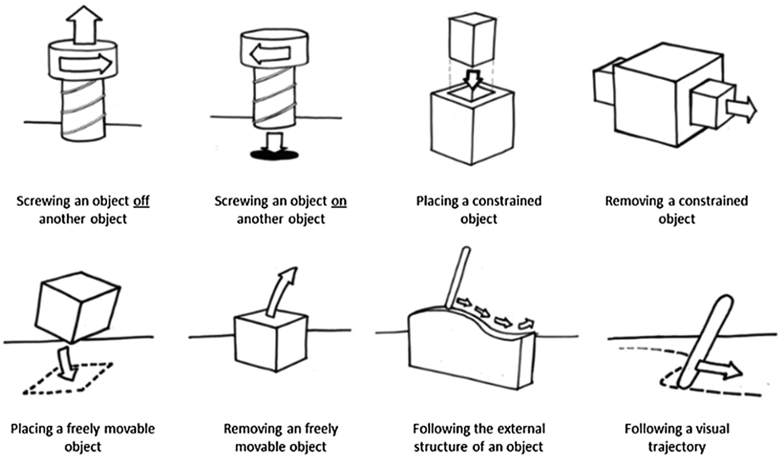

Fig. 1. Basic tasks included in our library for the remote Inspection, Repair and Maintenance use case.

The basic tasks cover most (but not all) movements made during IRM activities. This combination of tasks covers both translational and rotational movements. Tasks a through f can be done with either visual or haptic feedback, while the trajectory following tasks explicitly require tactile (task g) or visual (task h) information. The constrained object tasks (a through d) prompt a level of precision and subtleness from the system, while the freely movable tasks (e through h) can assess the speed of grosser movements.

3 Existing Dexterity Tests

Our approach is to adopt and where needed adapt already existing dexterous performance test from the relevant domains: robotics, rehabilitation, and occupational health.

3.1 Dexterity Assessment in Robotics Research

In the context of robotics, dexterity assessment is often done related to the isolated robotic system, or even only the end effector. This can be done by e.g. classifying kinematic properties of the system (Gosselin 1990), ticking off a dexterous manipulation taxonomy (Bullock et al. 2013) or a grasp taxonomy (Cutkosky 1989, Ruehl et al. 2014). Since we are developing a benchmark of the system as a whole, task-centric tests are more suitable. Most robotic systems in literature are tested using a custom test with specialized metrics for the system or use case at hand. Outside of academic literature, there are two ways in which the performance of robotic systems is contrasted and compared: standards and competitions.

Standards. A well-known robotics standard is ISO 9283 (1998), which considers manipulation with industrial robots in terms of precision, speed, repeatability and maximum load. Although this is an assessment of the robot's mechanics and not about the dexterous capabilities of the robot, we will adapt one of the patterns recommended by this standard for our tests (see Sect. 5). A more systems approach to haptic and tactile system evaluation (i.e. including the user and user experience) is advocated by ISO through ISO 9241 WG 9 (Van Erp and Kern 2008) but guidance for this topic is still under construction.

More domain-specific standardized tests can be found in the Standard Test Methods for Response Robots as formulated by the DHS-NIST-ASTM (Messina et al. 2009). This expansive array of tests includes mobility, safety, communications, sensors, underwater and aerial tests. The tests for manipulator dexterity are still under development, and not standardized yet. These tests are explicitly focused on EOD tasks: several for package-sized Improvised Explosive Devices (IEDs) and some for Personnel- and Vehicle-borne IEDs. The tests include aiming (touching an object in the right spot) and removing a cap, either by grasping it or pulling a wire. These tasks are part of our library of basic tasks.

Competitions. The robotics community has a long tradition of demonstrating robot capabilities in a competitive environment. Using tests from competitions would have the added value of some population data already being available. Two recent competitions that are specific to our field of application are the Argos Challenge (remote inspection and maintenance: http://www.argos-challenge.com/) and the ELROB 2016 (explosive ordnance disposal robots: http://www.elrob.org/). Unfortunately, the Argos challenge did not include manipulation tasks, and the ELROB does not publicly describe detailed tasks and results, underlining the importance to establish benchmark tests.

In more general applications there are two interesting competitions. The DARPA robotics challenge, which ended in 2015 (http://archive.darpa.mil/roboticschallenge/), included relevant and challenging tasks like opening a valve and cutting through drywall with a tool made for humans. The robots participating in this challenge can hardly be called teleoperated however, since their communications were deliberately limited and regularly cut off completely. This necessitated semi-autonomous solutions for all tasks. Secondly, the IROS 2017 Robotic Grasping and Manipulation Competition (http://www.rhgm.org/activities/competition_iros2017/) featured all sorts of tasks related to dexterous manipulation, including pouring water into a cup, placing connectors and assembling a set of gears. These tasks were supposed to be performed autonomously however, so there is no data on teleoperation performance. Although most tasks are more specific versions of our general basic tasks and only applied in (semi-) autonomous systems so far, we will use one task due to a lack of alternatives.

3.2 Dexterity Assessment in Rehabilitation and Human Factors Research

Besides robotics, dexterity is a common term in rehabilitation and other human related research fields (Yancosek and Howell 2009). Dexterity from a human perspective is also referred to as fine motor skills or the ability to make skillful, controlled arm-hand manipulations of objects (Makofske 2011). Dexterity in humans can be defined, taking a systems perspective, as the coordination of movements of lower arm and hand based on input from the visual system, the proprioceptive system and/or the haptic system. Various types of diseases can impair dexterity in humans, such as stroke, Parkinson's disease, cerebral palsy, other neurological disorders and trauma. The diminished dexterity in these patients is caused by impaired motor control and/or decreased sensory feedback, which has some overlap with the 'handicap' experienced in telemanipulation and caused by lack of transparency and sub-optimal control. This makes test to quantify reductions in fine motor skills also relevant for our goals.

Rehabilitation. Since dexterity and sensory integration (De Dieuleveult et al. 2017) are crucial for so-called 'activities of daily living (ADLs)', many tests are available from the rehabilitation domain. In patients with a sudden decrease in dexterity (for example following a stroke) it can be very valuable to know the extent of dexterity decrease, and possible increase during rehabilitation. Examples of dexterity tests are the Wolf Motor Function Test (WMFT, Wolf et al. 2001), the Chedoke Arm and Hand Activity Inventory (CAHAI, Barreca et al. 2005) and the Action Research Arm Test (ARAT, Yozbatiran et al. 2008). All three tests consist of several subtests and/or subscales testing grasp, grip, pinch and gross arm movements. Some subtests are ADLs, such as dialing 911, while other subtests are simple movements, such as placing the hand behind the head. The ARAT focusses on tasks can that be described as more basic movements, while the

CAHAI only consists of ADLs. The WMFT combines both types of tasks. The subtests included in the tests largely consist of movements that match the basic tasks in our library. The disadvantage is that they have to be performed by a (trained) physical therapist and are based on observer scoring. For the ARAT for example participants are scored between 0 and 3, where 0 is that the subject is not able to complete the task, while 3 is that the subject is able to perform the task in 5 s. Reference data are available for the WMFT, CAHAI and ARAT, however, the current way of scoring lacks sensitivity to discriminate current robot systems. Teleoperated robots are in general slower when performing a task compared to humans and the robots will perform the task less fluently/correctly. In the ARAT test, most robots will therefore score a 1 (able to partially perform the subtest in sixty seconds) or a 2 (able to perform the subtest, but slow), making it very hard to distinguish between the performance of different robots/robot modalities. To increase the discriminative power, scoring time needed or the number of repetitions in a certain timespan would be more suitable, but this reduces the usefulness of the reference data.

Occupational Research. Several dexterity tests were developed for dexterity assessment in occupational settings. Examples of such tests are the nine peg hole test (NPHT, Mathiowetz et al. 1985a), the Purdue pegboard test (PPT, Tiffin and Asher 1948), the box & block test (B&BT, Mathiowetz et al. 1985b) and the Minnesota rate of manipulation test (MRMT, Surrey et al. 2003). All these tests were developed at least 30 years ago to test dexterous performance of factory workers or dexterous performance of the general population. They all use rather abstract tasks (with good fits to our library), compared to the ADL inspired tasks used in rehabilitation. The advantage of occupational tests is that they are standardized, validated, have norms for a variety of populations, are commercially available and have a fine granularity in scoring (i.e. the number of pegs/blocks that can be moved in a certain timespan, or time to complete a task). This makes them also interesting for usage in robotics, allowing a unique way of benchmarking robotic dexterous performance.

4 Criteria for Subtest Selection

We used the criteria below to select the preferred test for each basic task in our library.

- Covers a basic task. A test should reflect one or more basic tasks. One basic task can be tested by more than one test.
- Has objective scores and sufficient discriminative power. The scoring of dexterous performance of teleoperated systems should preferably be objective and independent of observer (training). The sensitivity is high in the relevant range for teleoperated systems.
- Is clearly prescribed. This means that the methods of the test are simple and described in detail (preferably in literature), and the materials needed are easy to reproduce or obtain.
- Has population data/norms. Since we are striving for a benchmark test, comparison between systems or with specific populations is important.

5 Selected (Sub-)tests

Based on the criteria in Sect. 4, we selected the tests described and discussed below.

- Minnesota test. The Minnesota test (MT) has two versions that are very similar: the Minnesota rate of manipulation test (MRMT; 1969) and the Minnesota manual dexterity test (MMDT; 1991). The newer MMDT is most commonly used, although the MRMT standardization is better. Both MT's are produced by the Lafayette Instrument Company and both have boards with have 60 holes and feature the same instruction and scoring system. The MT consist of five subtests: placing, turning, displacing, one-hand turning and placing, and two-hand turning and placing test, all based on removing and placing blocks as fast as possible. The basic tasks performed in the MT are: (c) placing of a constrained object, (d) removing of a constrained object, and (f) removing a freely movable object. The MT also matches all the other criteria as described in Sect. 4. The MT is used in rehabilitation to establish baseline values for patients, and as a screening and selection tool in occupational health. Populations studied include stroke patients, children with cerebral palsy, COPD patients and upper-extremity amputees.
- Purdue pegboard test. The Purdue Pegboard test (PPT) was developed to select employees in industrial jobs such as assembly, packing and operation of certain machines. The PPT is produced by Lafayette Instruments Company and consist of four subtests, testing right hand, left hand, both hands and assembly performance. The first three test gross movements of hand and fingers, the forth also tests in-hand dexterity. In all subtests the subject has to place as many pegs as possible into (small) holes in a pegboard within a set time. The PPT is highly standardized and is used extensively in research and occupational practice. The basic tasks covered are included are: (c) placing a constrained object, and (f) removing a freely movable object. These basic tasks are also covered by the MT, but the objects that have to be grasped and the holes that the objects have to be placed in are significantly smaller with the PPT which makes it a valuable addition. The norm data available from the PPT is largely based on a relatively healthy and young population, but other populations include children, patients with Parkinson's disease, Huntington's disease and other types of brain injuries, patient with hand injuries and patients with a visual impairment.
- Box & block test. The Box & Block test (B&BT) was developed to fill the gap between the PPT and the MT. The B&BT requires a lower level of dexterity compared to the PPT, allowing also patient with a lower functioning level to be tested. Compared to the MMDT is the B&BT easier to perform, since its duration is shorter and the restrictions for the environment and subjects are less demanding. The aim of the B&BT is to move as many blocks as possible over an elevation (i.e. a standing board) in 60 s. The number of moved blocks is counted and represents the tests core. The test is not used in an occupational setting. Norms for the B&BT are available for the normal adult population, elderly, adults with neuromuscular problems and young school children. The basic tasks covered by this test are: (e) placing a freely movable object and (f) removing a freely movable object.

- ISO 9382 trajectory test. The ISO 9382 standard published in 1998 includes a pattern to assess the accuracy of a robot to follow a (pre-planned) trajectory as depicted in Fig. 2, and is an interesting option to test the basic tasks g) following the external structure of an object, and (h) following a visual trajectory. The deviations from the trajectory (maximum and average) for each part of the trajectory are monitored and represent the scores. The trajectory test based on the ISO 9382 pattern is not standardized to a degree such as the B&BT, MMDT and PPT and norms and population data are lacking.
- IROS subtest 10 (screwing test). For the basic tasks (a) screwing an object off another object and (b) screwing an object on another object, no standardized test is currently available meeting all our criteria. Our current plan is to adapt subtest 10 from the IROS 2017 challenge for service robots: open a bottle with a safety locking cap but with the bottle anchored onto a flat surface. The time to complete the task will be measured, resulting in an objective measure of performance. No norms are available for this test.

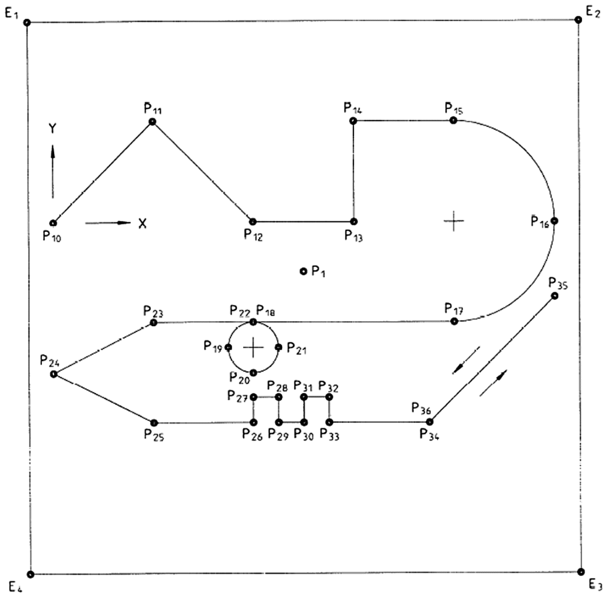

Fig. 2. The pattern as depicted in the ISO 9382 standard.

6 Discussion and Future Directions

One of the uses of the test battery is to assess which modalities of haptic feedback improve the system. The addition of haptic feedback to a teleoperated system likely aims at improving dexterous performance and this test battery will enable us to structurally and thoroughly test the added value of haptic feedback modalities. Haptic feedback that is too intense, or combinations of feedback that are too complicated may lead to decreased dexterous performance. Some forms of feedback on the other hand may be superfluous. The test battery will allow us to find the most useful modalities and level of haptic feedback for optimal dexterous performance. Our approach to define a library of basic tasks and select existing (sub-) tests turned out to work reasonably well, but several issues need attention.

Disturbing Effects of the Operator's Skill Level. The focus is of this paper is on dexterous performance of a complete teleoperated system, including the robot, the communication link and the operator. One of the difficulties that arise is the influence of the skill level and training of the operator on the system performance. Usually this is approached by either using operators that have no training or within-experiment training only (academic studies), or by using expert operators to get the best performance possible (industrial evaluations). Inter-operator differences can be bypassed by comparing an operator only with himself, attributing all differences in performance to the teleoperated system. This defeats one of the primary purposes of our tests however: comparing the test scores to norm data. We therefore suggest that each operator performs the task manually (without the teleoperated system) first as baseline, which will then be used as a normalizing value to estimate the performance of the teleoperated system on the task. Furthermore the difference between operators can also be minimized by including a homogenous group of participants with similar experiences with teleoperated systems. Finally, several tests (PPT, MT, B&BT) are repetitive. By analyzing the variation in performance of a single operation throughout the test, we can establish when a subject has finished training and improving.

From Unimanual to Bimanual. Most current teleoperated systems are unimanual (having a single effector), and our current library consists of unimanual basic tasks only. There may be good reasons to employ a bimanual robot (Smith et al. 2012), although the operation is more complicated. An interesting question is whether the increased mechanical capabilities of the robot can be sufficiently utilized by an operator to justify the addition of a second arm. Although not specifically designed towards this question, the proposed test battery may be suitable. There are three tests that can be performed in an uni- and bimanual mode (MT, PPT, and B&BT), allowing a comparison in performance of uni- and bimanual teleoperated systems for the current library. In addition, specific bimanual basic tasks may be added to the library, or current basic tasks may be modified into a bimanual version, for instance, screwing something of an object holding the object.

Calculate a Single Dexterity Measure. We selected five subtests of tasks, each with its own scoring method and procedure. It is not yet clear how these tests can be combined together to create a single dexterity measure. Calculating a general score for each test (like percentile) and establishing weightings over tests ultimately allows to calculate a single dexterity score.

Extending the Basic Task Library. Future extensions of the basic task library may include bi-manual tasks (as argued above), in-hand manipulation tasks, and other use-cases than the current IRM use case). In-hand manipulation is more common in human dexterity research than in robotics research, but may be useful to include for specific use cases and advanced robotic systems.

Scaling. The implicit assumption made in our approach is that we can transfer (human) dexterity tests to teleoperated robotic systems without scaling. However, the size and range of the robotic system does not necessarily have to be in the 'human' range but may be considerably smaller or larger. Although the basic tasks can be scaled accordingly, it is not a priori clear if and how the test protocols, norms, etc. should be adjusted. This requires further research.

Super-human Skills. A second implicit assumption is that the teleoperation test scores will be at best that of a healthy human but more likely in the range of that of children or even patients after a stroke or neuromuscular disease. However, there is no reason to restrict the performance of teleoperated systems to the normal human range, and robot speed, accuracy and stamina may (when combined with human dexterity and motor intelligence) ultimately result "super-human skills" that are outside the test range and norms. This may in the future force us to adjust the tests, the scoring, and the norms.

Restrictions. One skill that is not typically part of the definition of dexterity is the fine control of exerted force. This skill is reflected in the basic tasks, but specific tests may result in clearer insight in its role in dexterous performance. Lack of accurate force control may hamper dexterous performance, for instance through dropping objects. The second restriction is that we focus on the telemanipulation part of teleoperation, while teleoperation performance also depends on the telesensing part. For instance, better situational awareness (view on the workspace), better self-awareness (proprioception, localization, eye-hand coordination), and better platform movement (positioning for the task), may all contribute to the teleoperation performance. Finally, for telemanipulation, there is more to dexterity than pure object manipulation. Discovery of an object's texture, weight, size and/or temperature may be valuable in some cases, and is not tested for by our benchmark.

7 Conclusions

This paper describes the first step towards benchmarking the performance of teleoperated systems. After surveying the literature in the research fields of robotics, rehabilitation, occupational research and haptics a set of five subtests was selected. All subtests met at least three out of four of the defined criteria: (1) testing one or more basic tasks, (2) objectively measured, (3) described in detail and (4) norm data being available. The selected subtests are the Box & Block test, the Purdue Pegboard test, the Minnesota Manual Dexterity test, the ISO 9382 trajectory test (based on the ISO 9382:1998 standard) and the adapted version of the screwing subtest of the IROS 2017 service robots challenge.

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