Shadow Teleoperation System

Technical Specification

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1 Overview

The Shadow Teleoperation System combines state-of-the-art robotics and user interface technologies in order to mimic human arm and hand movements, and allow highly intuitive human-level dexterity at distance.

The robot is comprised of two 6 degree-of-freedom (DoF) arms, each fitted with our 20 DoF (24 joint) Dexterous Hand, for a combined total of 52 DoF (60 joints). The 6 DoF arms allow the system to mimic any position and orientation of the user's forearms, and the Dexterous Hands' humanoid kinematics allow accurate reproduction of the user's hand movements, including wrist angles.

The main user interface is the Shadow Glove, which tracks the user's forearm, palm and fingertips in 6 DoF each, using a combination of optical and magnetic sensors. The state of the system is controlled by a foot pedal, allowing the user to start, stop and reset the system. Its main function is that of a "clutch", expanding the workspace of the robot beyond that of the user.

The system has been designed to provide comparable movement precision to the human performance level. It has the potential to not only reduce travel costs and eliminate skill shortages, but remove humans from dangerous situations entirely.

To summarise, a standard Shadow Teleoperation System includes:

- Robots and control systems:
  - Two Shadow Dexterous Hands
  - Two Universal Robots UR10e 6-DoF arms
  - Two Universal Robots CB3 control boxes
  - A dedicated robot control computer, running a real-time kernel
  - A main computer, running main teleoperation processes
  - 2+ emergency stop buttons
- User interface:
  - Two Shadow Gloves and interfaces/adaptors
  - A 3-button USB control pedal
  - An emergency stop pedal
  - A HTC Vive Pro
  - Two HTC Vive Trackers (v3)
  - Four HTC Vive Base Stations (v2)
- A gigabit router connecting all networked devices
- Shadow Teleoperation software and documentation, installed on the above computers
- All necessary power supplies, cabling etc.

2 Mechanical Profile

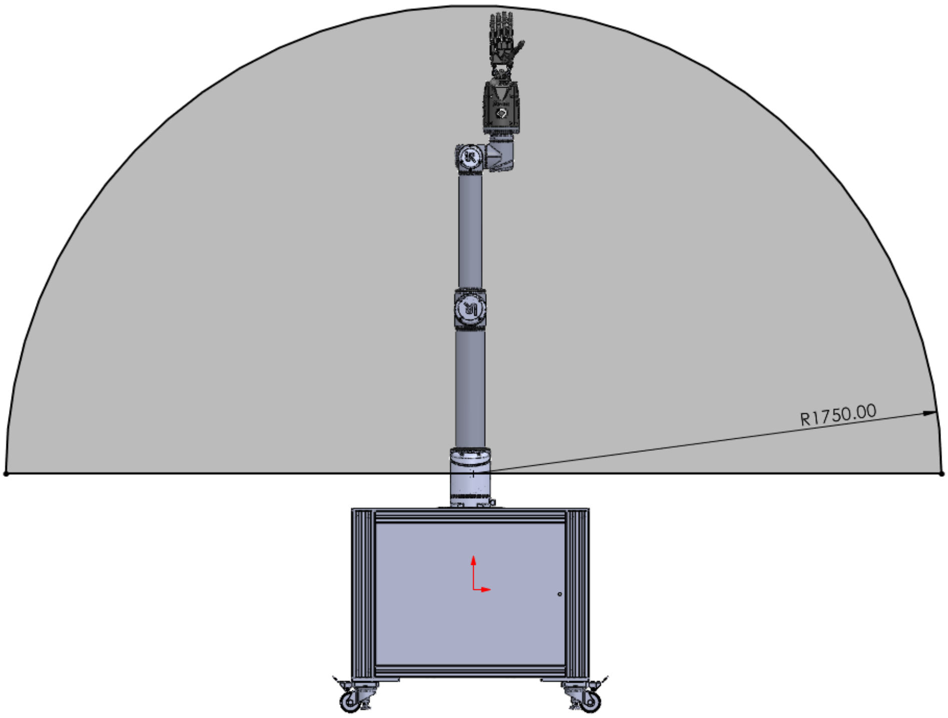
2.1 Robot kinematic structure

2.1.1 Arms

The Shadow Teleoperation System kinematics are optimised to be as close as possible to the kinematics of the human upper limbs. Each arm is fixed to a heavy stand that elevates the base of the robot arm to 75 cm above the floor, and keeps the system stable. The standard distance between both robot arms is 2 meters; it can be adapted according to requirements.

Joints	Working range		Maximum Speed
	Min	Max	
Arm Wrist 3	-360°	360°	180°/s
Arm Wrist 2	-360°	360°	180°/s
Arm Wrist 1	-360°	360°	180°/s
Arm Elbow	-360°	360°	180°/s
Arm Shoulder	-360°	360°	120°/s
Arm Base	-360°	360°	120°/s

Joint maximum speeds are based on factory tuning and control parameters; the values listed here are indicative. Speeds will vary if tuning and control parameters are changed.



It should be noted that arm control is impaired at full extension, a universal problem in inverse kinematics, and the practical workspace of the arm is in fact slightly smaller than indicated.

2.1.2 Hands

The Dexterous Hand kinematics are optimized to be as close as possible (within engineering constraints) to the kinematics of the human hand.

Joints	Working range		Maximum Speed
	Min	Max	
Finger Distal (F1)	0°	90°	160°/s
Finger Middle (F2)	0°	90°	
Finger Base Abduction (F3)	-15°	90°	200°/s
Finger Base Lateral (F4)	-20°	20°	130°/s
Little Finger Rotation (LF5)	0°	45°	140°/s
Thumb Distal (TH1)	-15°	90°	200°/s
Thumb Middle (TH2)	-30°	30°	140°/s
Thumb Middle Lateral (TH3)	-12°	12°	100°/s
Thumb Base Abduction (TH4)	0°	70°	120°/s
Thumb Base Rotation (TH5)	-60°	60°	170°/s
Hand Wrist Abduction (WR1)	-40°	28°	70°/s
Hand Wrist Lateral (WR2)	-28°	8°	50°/s

Joint maximum speeds are based on factory tuning and control parameters; the values listed here are indicative. Speeds will vary if tuning and control parameters are changed.

The thumb has 5 degrees of freedom and 5 joints. Each finger has 3 degrees of freedom and 4 joints.

The distal joints of the fingers are coupled in a manner similar to a human finger, such that the angle of the middle joint is always greater than or equal to the angle of the distal joint. This allows the middle phalange to bend while the distal phalange is straight. The little finger has an extra joint in the palm provided to allow opposition to the thumb.

All joints except the finger distal joints are controllable to +/- 1° across the full range of movement.

2.2 Tracking

By combining the below data, the Shadow Teleoperation System software establishes the room-scale positions and orientations of the user's forearm, palm, fingers and thumb.

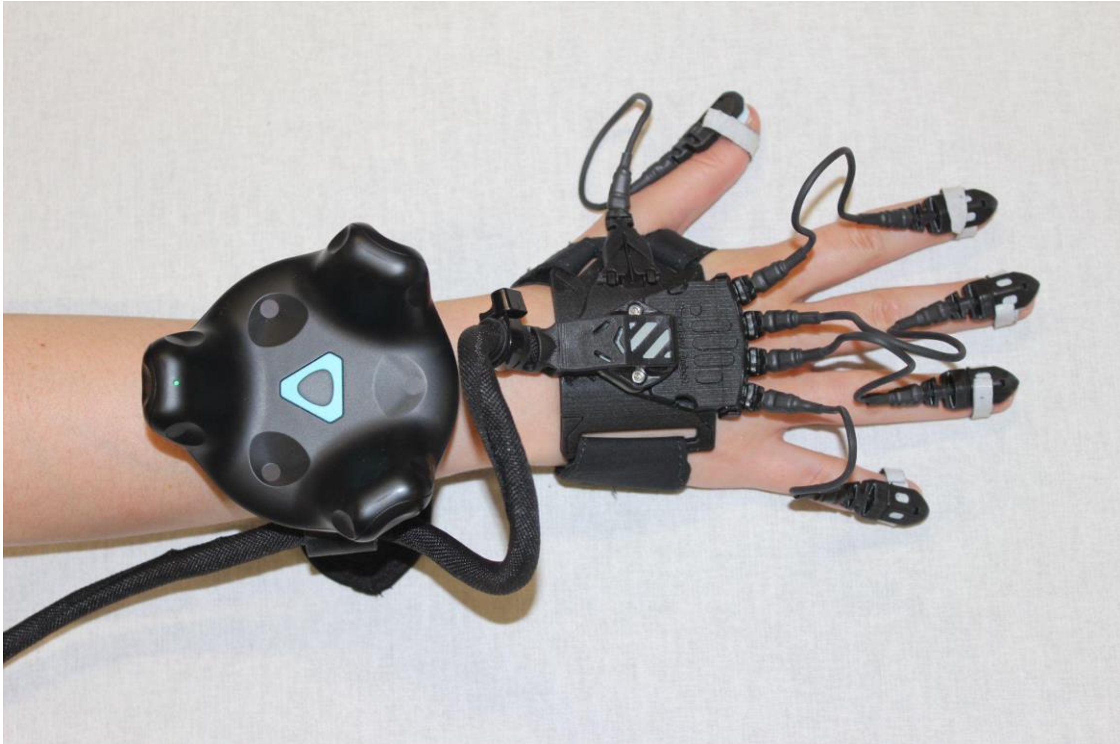
2.2.1 Arms

The user's palms are tracked using a HTC Vive laser tracking system, which reports the positions of trackers attached to the Shadow Glove. The Vive system uses 4 base stations, each with a 120º field of vision, to provide room-scale tracking with minimal occlusions. The base stations can be reconfigured to suit the user's workspace and typical range of movement, but this is usually unnecessary.

2.2.2 Hands/Gloves

The system includes a pair of Shadow Gloves, which are used to track the user's finger movements. The gloves are designed to be comfortable for a wide range of hand sizes, while allowing full, unencumbered finger movement; no grasp or gesture is impossible to perform while wearing the Shadow Gloves.

A total of 36 degrees of freedom are tracked. Each glove contains six 6 DoF (x, y, z, roll, pitch, yaw) electromagnetic motion trackers; one in each finger tip, and one on the forearm. These provide precise and repeatable tracking of finger and forearm position and orientation relative to the palm, with an accuracy of 0.38mm and 0.1° RMS at 240Hz.



2.3 Weight and Payload

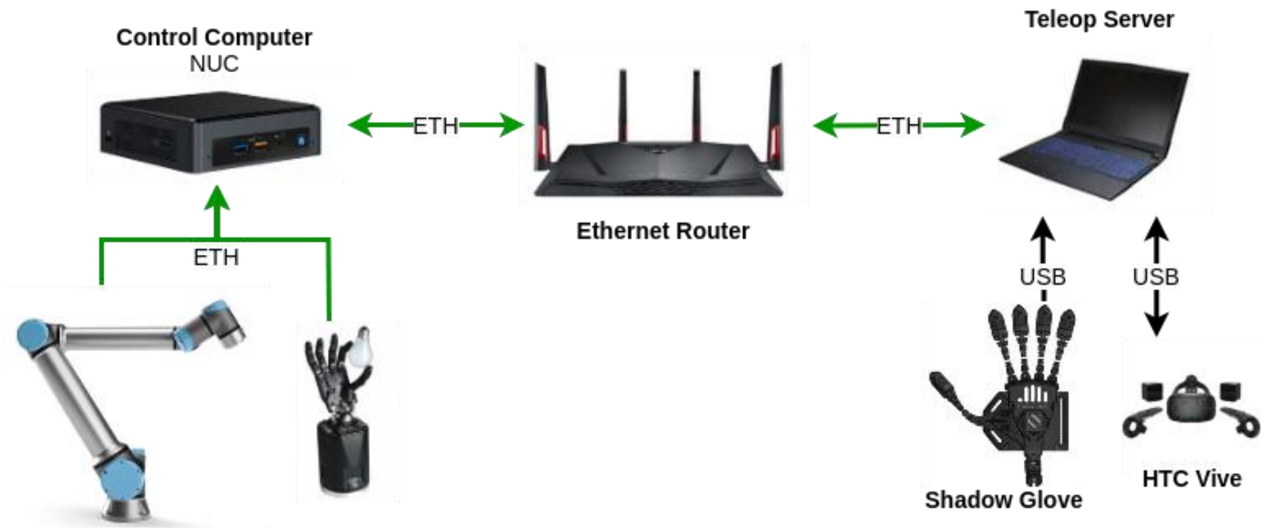
Component	Mass /kg	Quantity	Total Mass /kg
UR10e Arm	33.5	2	67
UR CB3 Control Box	12	2	24
Shadow Dexterous Hand	5	2	10
Stand	75	2	150
Stand ballast	50	2	100
Total	**-**	**-**	**351**

The robot teleop system has a total weight of 251kg. An additional 50kg will have to be added per stand if the system cannot be bolted to the floor. The system allows the operator to lift and manipulate objects up to 3kg, although this is heavily dependent on grasp shape.

2.4 Safety

Despite being designed for remote teleoperation, the Shadow Teleoperation System is safe even when the robot is sharing a workspace with humans. The Universal Robots UR10e is a collaborative robot, built from the ground up to safely share a workspace with humans. The Shadow Dexterous Hand is (configurably) compliant, and constantly monitors and limits tendon forces.

3 Communications



4 Computers and Software

The system is supplied with a multi-core discrete-GPU laptop running Ubuntu, a NUC for robot control and a router to connect them. The router allows later reconfiguration for remote teleoperation. Shadow Teleoperation software is installed on both computers. The software is based on the ROS meta-operating system.

The system is delivered pre-configured; teleoperation can be initiated using the graphical interface on the main computer. Users can also launch fully or partially simulated teleoperation systems, run demonstrations, etc.

4.1 Open platform

For customers wishing to adapt or extend the Shadow Teleoperation System, the open nature of the infrastructure of the system lends itself to such projects.

- The software is separated into ROS nodes, launched using launch files, communicating via ROS topics, services etc.
- Launch files can be modified, node arguments and parameters modified
- Topics can be subscribed to, remapped, etc.
- The software is containerised using Docker, affording it an isolated environment to run in, and protecting it from e.g. environmental changes that may be necessary for additional customer software
- Source code for our open-source software is included. Some software is proprietary and closed-source, but all communication between nodes is exposed via ROS
- Source code for the dexterous hand micro-controllers and schematics for the electronics subsystems are available on request under Non-Disclosure Agreement (NDA).
- Example code along with documentation is provided, along with access to e-mail support from Shadow.
- 3D models and kinematic data are supplied via ROS.
- Collision scenes, robot models etc. are all defined using ROS-standard methods (MoveIt! scene files, URDFs etc.) and can be modified

5 Specification Summary

Item	Value
Mass	140kg
Stand ballast (per stand, if not bolted to floor)	50kg
Payload (per hand)	3kg
Max speed (arm)	$1ms^{-1}$
Max speed (hand)	~1Hz (Fully open to fully clenched)
Power (peak)	2.3kW
Input Voltage	110 - 240V
User-robot latency (movement start-to-start)	50ms
Degrees of freedom (per hand)	20
Degrees of freedom (per arm)	6
Degrees of freedom (total)	52
Operating temperature range	10 - 40°C
Operating relative humidity (non-condensing)	0 - 90%

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