MERIt
A Multi-Elastic-Link Robot Identification Dataset

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1 About MERIt and this document

At TU Dortmund the Institute of Control Theory and Systems Engineering **(RST)** has developed the three degree of freedom experimental setup **TUDOR** detailed in section 3. During research with this experimental platform a number of measurements have been collected for kinematics as well as dynamics identification. In our opinion the research in elastic link robots suffers from the very limited number of experimental setups being available in the world. Among the few existing experimental setups even fewer are multi-link arms. Most setups operate in a horizontal plane in order to eliminate the effect of gravity on the mechanism dynamics. At the current state the control of elastic link arms is a fundamental research topic. Many promising theoretical concepts, which can be found in literature, still have to prove their value in experimental evaluations before they can enter practical applications. However, the development and maintenance of an experimental setup is a challenging, costly and time consuming technical burden coming on top of the actual scientific workload. The idea behind **MERIt** is to make the measurement data freely available for other researchers working in the modeling and control of elastic link robots without having a direct access to a real experimental setup. This document is a manual to the contents of **MERIt** .

2 How to use MERIt

The **MERIt** is made freely available in the hope that it is useful for other researchers in their work on elastic link mechanism modeling and control or perhaps general system identification topics. If you wish to use the **MERIt** , please add a reference in your publications. A reference should look like:

Malzahn, J. and T. Bertram: MERIt - A Multi-Elastic-Link Robot Identification Dataset, *Institute of Control Theory and Systems Engineering (RST), TU Dortmund, Germany*. URL: `http://tinyurl.com/TUDOR-MERIt`, date of last check, dataset name.

The **MERIt** is intended to continously develop over time. If you have access to an experimental setup **we encourage you to contribute additional data** to the **MERIt** . Any real elastic link arm is greatly welcome. Contributions will get suitably acknowledged.

The **MERIt** is organized in MATLAB `iddata` objects since MATLAB is the tool we use for the development of our models and control algorithms. All `iddata` objects comprise multiple realizations of the same experiment in a conveniently compact and documented data structure. However, if you do not own a recent MATLAB System Identification Toolbox license, you can access the data using Octave. Octave loads the data as structures. An alternative organisation of the measurements in HDF5 files is currently under consideration. In exceptional situations we could offer to convert the data format to CSV files upon personal request.

3 The experimental setup TUDOR

Figure 1 (**a**) depicts a photograph of the experimental setup **TUDOR** (Technische Universität Dortmund Omni-elastic Robot). The equivalent rigid body kinematics are illustrated in figure 1 (**b**). The top view schematic in figure 1 (**b**) depicts the locations of the strain sensors applied to the individual links. If you wish to see TUDOR in action watch our videos on YouTube (`http://youtu.be/kJPuenyxeps`).

Joints and Links

TUDOR is a 3 degree-of-freedom robotic arm. The actuators are brushless DC motors with planetary gears and ceramic quadrature encoders. The gear ratios are 156:1, 230:1 and 246:1 from the first to the third joint. The vendor specifies the gear backlash to be less than one degree. The first actuator with the joint variable q_1 is installed on the cylindrical base, and rotates the arm structure in the horizontal plane around the axis z_1. The mechanical connection between the first and second joint is considered to be the rigid first link of the robot. The second and the third joints have horizontal rotary axes with q_2 about z_2 and q_3 about z_3. Both actuators are interconnected via the elastic second link. The elastic third link is connected to the third actuator. The elastic links are spring steel rods with rectangular shaped cross sections with a width of 15 mm and a height of 4 mm. The parameters of the joints and links are summarized in the table at the end of this section.

The strains are measured at ${}^2x_{s,1} = 46\,\text{mm}$, ${}^2x_{s,2} = 260\,\text{mm}$, ${}^3x_{s,1} = 45\,\text{mm}$ and ${}^3x_{s,2} = 235\,\text{mm}$. The length of the link clamp along the x-direction amounts to 31 mm on link 2 as well as 28 mm on link 3.

External Stereo Camera Setup

For assessment of the endeffector motion, two colored spheres can be mounted at the tip. These spheres are located in the image pairs of a stereo camera setup mounted under the lab-

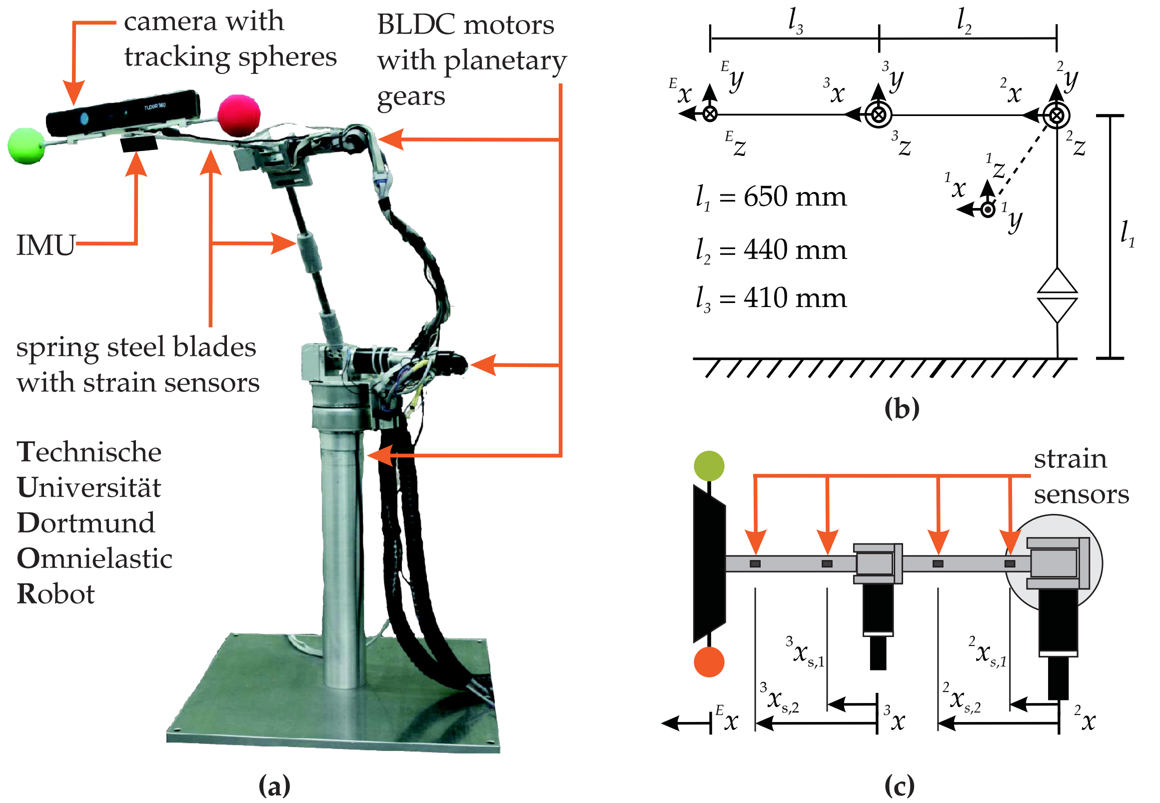

Figure 1: Photograph of the multi-elastic-link robot arm TUDOR (**a**) with equivalent rigid body kinematics (**b**) and top view schematic (**c**) including the strain sensor locations.

oratory ceiling. The stereo image pairs consisting of two images with a resolution of 640x480 are recorded at a rate of 50 Hz. The image processing takes place offline. The localization accuracy is 2 mm.

RGB-D Sensor

For research in visual servoing of elastic link arms and camera based oscillation damping, an RGB-D sensor can be mounted at the tip. The IMU is fixed to the RGB-D sensor as a reference for camera based oscillation sensing algorithms.

Payload

In dynamics identification datasets with different payloads the camera unit is replaced by a variable number of test mass plates. The dimensions of each plate are 2 mm by 80 mm by 80 mm. The mass of each plate amounts to 100 g.

Computer Hardware

The controllers and synchronous data acquisition are realized on a standard PC running a MATLAB xPC target real-time operating system. Another Desktop PC operates in soft real-time. It serves as console to send motion commands and upload offline generated stimuli via TCP/IP. After the upload, the stimuli are then executed in hard real-time on the xPC.

link parameter	**symbol**	**unit**	**link 1**	**link 2**	**link 3**
length	l_B	mm	0	430	410
width	b_B	mm	0	15	15
height	$2\,y_b$	mm	0	4	4
density	ρ_b	10^3kg/m^3		7.8	7.8
Youngs modulus	E	10^9 N/m^2		200	200

joint parameter	**symbol**	**unit**		**actuator 1**	**actuator 2**	**actuator 3**
model				EC-max 40	EC-max 40	EC-max 30
overall length	l_M		mm	185.3	198.8	150.9
Ø motor	d_M		mm	40	40	30
Ø gear	d_G		mm	52	52	32
gear ratio	n_M			156:1	230:1	246:1
gear backlash			deg	<1	<1	<1
rotor and gear inertia*	I_M	10^{-6}	kgm^2	9.19	9.41	0.82
pos. viscous friction*	k_v^+	10^{-5}	Nms/rad	2.21	1.86	0.26
neg. viscous friction*	k_v^-	10^{-5}	Nms/rad	2.11	1.86	0.23
pos. coulomb friction*	k_c^+	10^{-3}	Nm	0.46	3.34	1.49
neg. coulomb friction*	k_c^-	10^{-3}	Nm	7.25	1.15	2.40
torque constant	k_τ	10^{-3}	Nm/A	44.8	44.8	12.9
joint ranges			deg	$[-170, 180]$	$[-14, 192]$	$[-102, 102]$
maximum speed			deg/s	184	125	146
max. continous current			A	3.95	3.95	2.85
max. intermittent current			A	11.85	11.85	8.55
max. continous torque			Nm	30	30	6
max. intermittent torque			Nm	45	45	7.5
encoder resolution			1/rev.	500	500	500
amplifier gain*	k_{amp}		A/V	1.39	1.39	1.39
amplifier cut-off frequency*	ω_{amp}		Hz	833	833	833
mass*			kg	0.5410	1.6680	0.5885

Parameters marked with an asterisk (*) have been experimentally identified for th particular joint. All other parameters are taken from the vendor's datasheets. Joint ranges, maximum joint speeds as well as continuous and intermittent torques are referred to the gear output.

4 Contents of the MERIt

The **MERIt** is organized in MATLAB `iddata` objects. In general, the inputs and outputs are defined as:

Inputs	Unit	Description
$q_{c,1}$	rad	commanded joint angle, first joint
$q_{c,2}$	rad	commanded joint angle, second joint
$q_{c,3}$	rad	commanded joint angle, third joint
Outputs	**Unit**	**Description**
q_1	rad	actual joint angle, first joint
q_2	rad	actual joint angle, second joint
q_3	rad	actual joint angle, third joint
dq_1	rad/s	joint angular velocity, first joint
dq_2	rad/s	joint angular velocity, second joint
dq_3	rad/s	joint angular velocity, third joint
I_1	A	motor current, first joint
I_2	A	motor current, second joint
I_3	A	motor current, third joint
eps_{21}	μm/m	strain measured on the second link at ${}^2x_{s,1}$ (see fig. 1(**c**))
eps_{22}	μm/m	strain measured on the second link at ${}^2x_{s,2}$(see fig. 1(**c**))
eps_{31}	μm/m	strain measured on the third link at ${}^3x_{s,1}$ (see fig. 1(**c**))
eps_{32}	μm/m	strain measured on the third link at ${}^3x_{s,2}$(see fig. 1(**c**))
ddq_1	rad/s^2	joint angular acceleration, first joint (noisy)
ddq_2	rad/s^2	joint angular acceleration, second joint (noisy)
ddq_3	rad/s^2	joint angular acceleration, third joint (noisy)

The following description details the individual subsets and tools provided with **MERIt** :

Dataset TUD01 – APRBS responses without damping: For the identification of the undamped dynamics this dataset consists of responses to various amplitude-modulated pseudo-random binary stimuli (APRBS). APRBS are generic stimuli and frequently used for the identification of nonlinear dynamics systems. Note, the data set focuses on the elstic links. Hence, the first joint is kept in the zero pose while individual independent APRBS are simultaneously applied to the second and third joint. The joints are position and velocity controlled based on a $\sin^2$ shaped acceleration profile. There is no active oscillation damping. The motions cover the entire robot workspace and joint dynamics range. **TUD01** is realized with 0 g to 400 g payload. Each realized experiment has a duration of 80 seconds.

Dataset TUD02 – APRBS responses with damping: The dataset is created in the same way as **TUD01**. However, oscillation damping by Malzahn et al. (2011) is activated this time. The dataset forms the basis of the damped dynamics identification by Malzahn, Reinhart, and Bertram (2014). Responses are available with 0 g to 400 g payload.

Dataset TUD03 – Static joint configurations: The data included in **TUD03** has been recorded to investigate the static deflections with different masses throughout the entire robot workspace. Again, the first joint is kept fixed at zero configuration. The operating range of the second and third joint are sampled in 30 degree steps. The payload varies from 0 g to 500 g. Each realized experiment has a duration of 15 seconds.

Dataset TUD04 – Static end effector poses: Phung et al. (2011) present a data driven approach to model the forward and inverse kinematics of TUDOR. The data used in this work is **TUD04**, which samples the planar workspace of TUDOR with $q_1 = 0°$ while using a stepsize of 10° for $q_2 \in [0°; 180°]$ as well as for $q_3 \in [-90°; 90°]$. This results in a total number of 361 sampling points for each payload between 0 and 400 grams. The distribution of the individual data points is exemplified in figure 2.

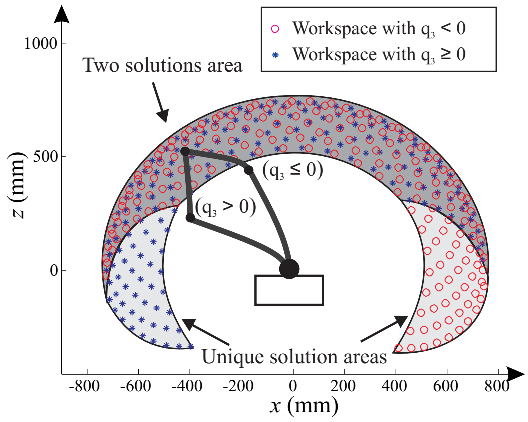

Figure 2: Example distribution of the data samples.

In the equilibrium state of every individual joint configuration the strain signals eps_{21} and eps_{31} are recorded along with the end effector position obtained from the external stero camera setup. As a result the input/output definition of subset **TUD04** slightly differs from the general scheme described above:

Inputs	**Unit**	**Description**
$q_{c,1}$	rad	commanded joint angle, first joint
$q_{c,2}$	rad	commanded joint angle, second joint
$q_{c,3}$	rad	commanded joint angle, third joint
Outputs	**Unit**	**Description**
eps_{21}	μm/m	strain measured on the second link at ${}^2x_{s,1}$ (see fig. 1(**c**))
eps_{31}	μm/m	strain measured on the third link at ${}^3x_{s,1}$ (see fig. 1(**c**))
${}^0X_E$	m	end effector X position w.r.t. robot base
${}^0Y_E$	m	end effector Y position w.r.t. robot base
${}^0Z_E$	m	end effector Z position w.r.t. robot base

Note: The MATLAB `iddata` object is actually intended to store time series or frequency domain data for system dynamics identification. However, **TUD04** provides static samples without any temporal relationship. For consistency with the rest of **MERIt** , the `iddata` objects just work as a container with a dummy default sampling time of 1 second.

Experiment Inspection Tool For quick inspection a small graphical tool is provided with the **MERIt** . It can be found in the m-file `experimentInspector.m` and should be self explaining. Figure 3 displays an example, where the time series of the joint value and the angular velocity for the second joint are plotted along with the strain measured on the second link. The plots represent the third repetition of the experiment **TUD02** with a payload of 200 g.

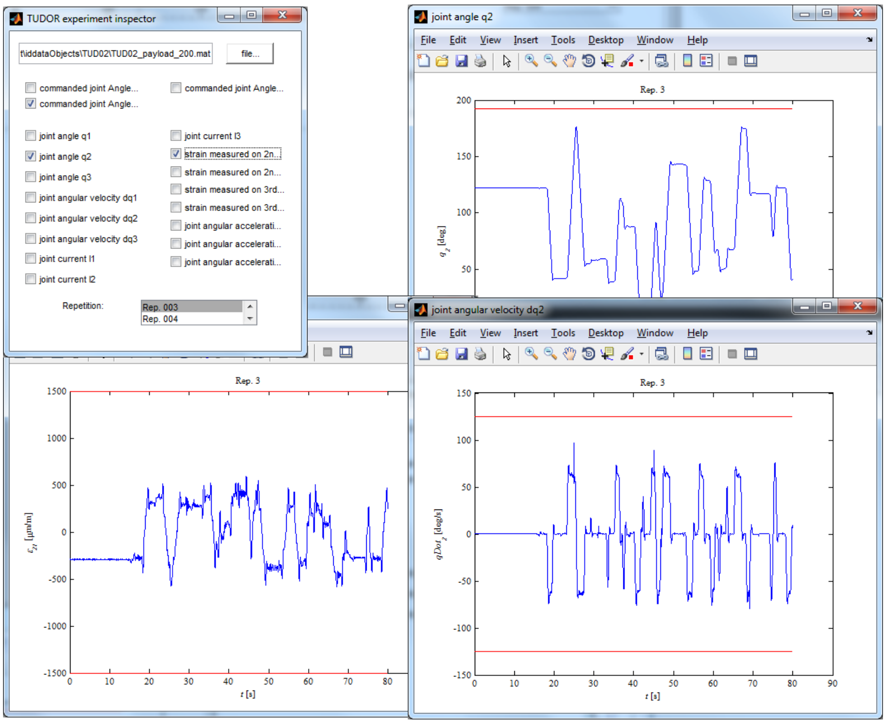

Figure 3: Experiment inspection tool provided with **MERIt**

5 Acknowledgments

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Phung, A. S., J. Malzahn, F. Hoffmann, and T. Bertram (2011). "Data based kinematic model of a multi-flexible-link robot arm for varying payloads". In: *International Conference on Robotics and Biomimetics*, pp. 1255–1260.

Change log

October 07, 2014: TUD04 added

September 23, 2014: Typos corrected in torque constant units. Thanks to Bruno Scaglioni.