

Table 11: Variable Definitions

Variable	description	unit
\min	minimum value of a set	-
\mathbf{F}_s	sensed force vector	N
μ	mean value	-
N	number of trials	-
σ	standard deviation	-
t	measured time	s
t_m	time where minimal motion was achieved	s
\mathcal{T}	set of time values	s
x	travelled distance	mm
x_1	point where the acceleration phase finished	mm
x_2	point where the entire motion finished	mm

Table 12: Metric Definitions

Metric	name	description	eq.	unit	best ⁴
MF	Minimum Motion Force	minimum required force to initiate motion in x-direction	$\ \mathbf{F}_{s,x}(t_m)\ ,$ $t_m = \min(\mathcal{T}),$ $\mathcal{T} = \{t \mid \ \mathbf{x}(t)\ = 0.1 \text{ mm}\}$	N	0.1
GF	Guiding Force	average force required to guide end-effector with 250 mm/s in y-direction	$\frac{1}{N} \sum_{i=1}^N \mu_{\ \mathbf{F}_{s,x}\ }$	N	0.1
GD	Guiding Force Deviation	standard deviation of force required to guide end-effector with 250 mm/s in y-direction	$\frac{1}{N} \sum_{i=1}^N \sigma_{\ \mathbf{F}_{s,x}\ }$	N	0.1
ME	Maneuver Effort	energy required to manually accelerate the robot to final guiding speed of 250 mm/s	$\frac{1}{N} \sum_{i=1}^N \int_0^{\mathbf{x}_1} \mathbf{F}_{s,x} d\mathbf{x}$	J	0.1
GE	Kinesthetic Guidance Energy	effort required from the human operator to move the robot end-effector from one side of the workspace to the other side	$\frac{1}{N} \sum_{i=1}^N \int_0^{\mathbf{x}_2} \mathbf{F}_{s,x} d\mathbf{x}$	J	0.1

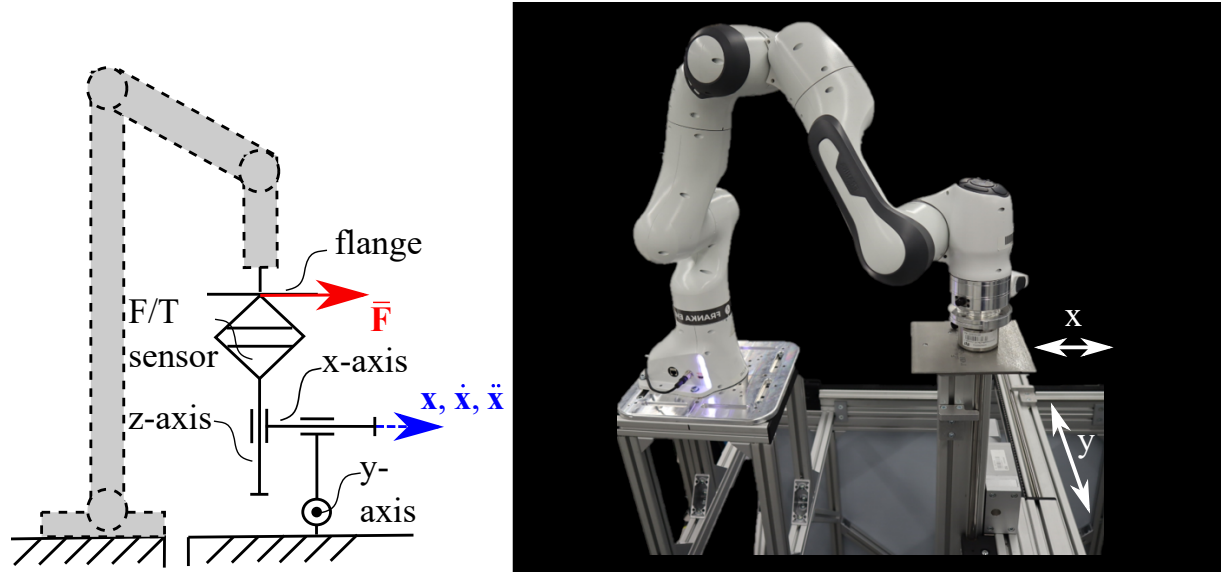


Figure 14: Test gantry for maneuverability metrics. Depicted on the left is the sensing principle and on the right is the test stand used for the conducted experiments.

Table 13: Setup definitions

component	considered quantity	value	accuracy req.
start position x_s (MF)	position in robot Cartesian coordinates based on reference cube [mm]	C1	± 2
start position x_s (rest)	position in robot Cartesian coordinates based on reference cube [mm]	C1E1	± 2
linear motion resolution	position [mm]	-	± 0.1
trajectory (MF)	acceleration [mm/s ²]	1	± 0.1
	velocity [mm/s]	-	-
	distance [mm]	20	± 0.1
acceleration (rest)	position [mm/s ²]	1000	± 1
	velocity [mm/s]	250	± 1

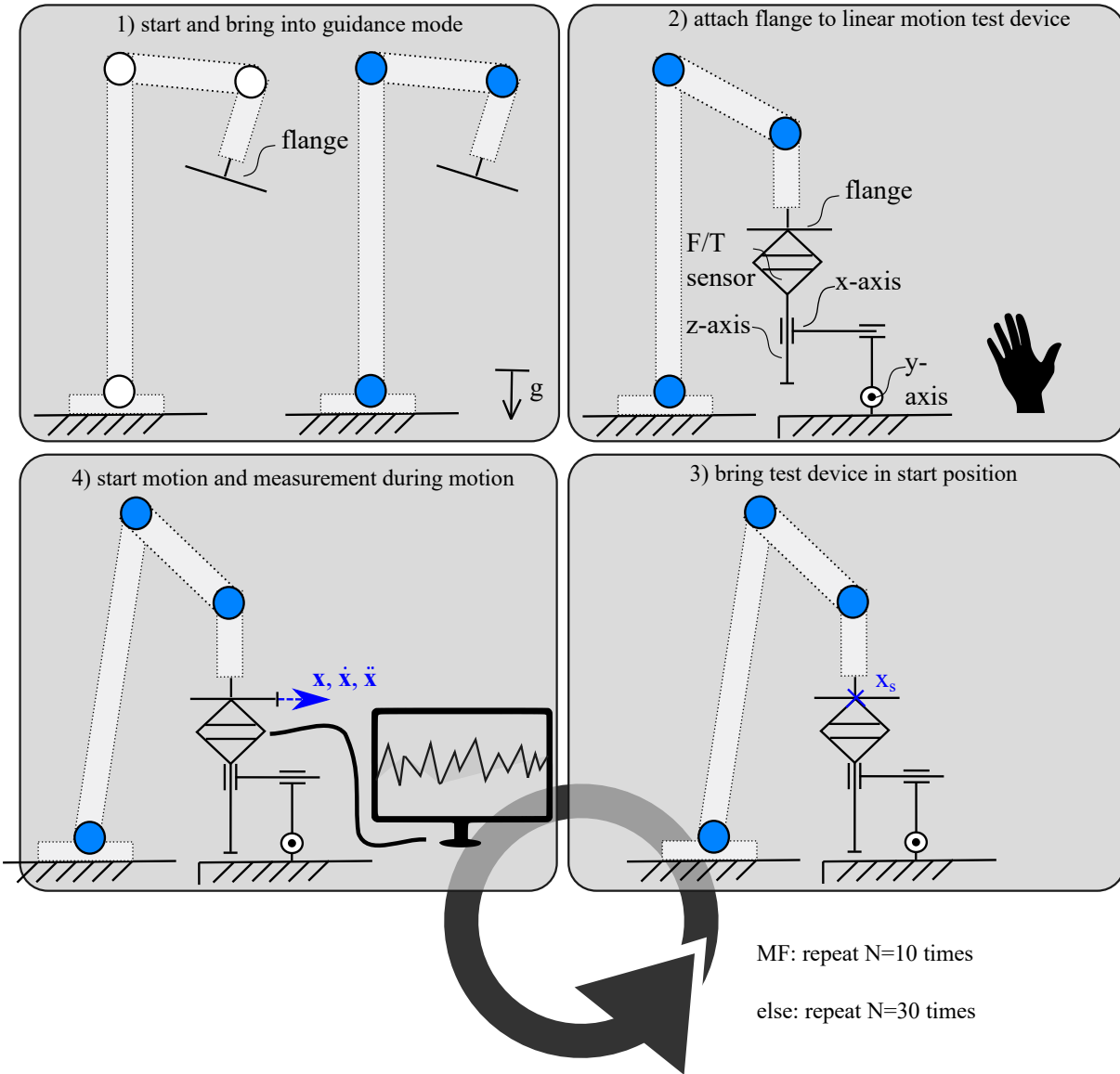


Figure 15: Measurement Procedure for GF , GD , ME , and GE .