Force Control Fitness Metrics

Table 4: Variable Definitions

Variable	description	unit
f	frequency	Hz
$\mathcal{F}$	set of frequencies	Hz
$\max$	maximum value of a set	-
$\mathbf{F}_{\mathrm{d}}$	desired force vector	N
$\mathbf{F}_{\mathrm{s}}$	sensed force vector	N
$\mathbf{F}_{\mathrm{set}}$	force measured after settling time was reached	N
μ	mean value	-
N	number of trials	-
N_{s}	number of trials where force successfully settled	-
σ	standard deviation	-
t	measured time	s
$\mathcal{T}$	set of time values	s
Z	ratio between measured and desired force	-

Table 5: Metric Definitions

Metric	name	description	eq.	unit	best[2]
A_{cF}	Force Controller Accuracy	deviation between desired force and maximum values of $3\,\mathrm{s}$ applied force	$\max_N\left(\max_t\left\lvert\lVert\mathbf{F}_{\mathrm{s}}\rVert-\lVert\mathbf{F}_{\mathrm{d}}\rVert\right\rvert\right)$	N	0.1
P_{cF}	Force Controller Precision	repeatability of the maximum values of $3\,\mathrm{s}$ the applied force in 30 trials	$\mu_{\mathbf{l}_{\mathrm{c}}}+3\sigma_{\mathbf{l}_{\mathrm{c}}}$, $l_{\mathrm{c,i}}=\max_N\lVert\mathbf{F}_{\mathrm{s}}\rVert-\frac{1}{N}\sum_{i=1}^{N}\max_t\lVert\mathbf{F}_{\mathrm{s}}\rVert$	N	0.01
RS_{F}	Force Controller Resolution	force fluctuation within one force application over $3\,\mathrm{s}$	$\max_N\left(\max_t\lVert\mathbf{F}_{\mathrm{s}}\rVert-\min_t\lVert\mathbf{F}_{\mathrm{s}}\rVert\right)$	N	0.01
OV	Force Controller Overshoot	overshooting in quasi-static contact starting $1\,\mathrm{mm}$ above surface	$\max_N\left(\max_t\left\lvert\lVert\mathbf{F}_{\mathrm{s}}\rVert-\lVert\mathbf{F}_{\mathrm{set}}\rVert\right\rvert\right)$	N	1
TS	Force Controller Settling Time	settling time in quasi-static contact starting $1\,\mathrm{mm}$ above surface	$\max_N(\max(\mathcal{T}))$, $\mathcal{T}=\{t\mid\lVert\mathbf{F}_{\mathrm{s}}(t)\rVert=1.03\lVert\mathbf{F}_{\mathrm{set}}\rVert\vee\lVert\mathbf{F}_{\mathrm{s}}(t)\rVert=0.97\lVert\mathbf{F}_{\mathrm{set}}\rVert\}$	s	0.01
MAF	Minimum Applicable Force	minimum applicable force in quasi-static contact starting $1\,\mathrm{mm}$ above surface	$\max_N(\max_t\lVert\mathbf{F}_{\mathrm{s}}\rVert)$	N	0.1
B_{c}	Controller Bandwidth	bandwidth of force controller in quasi-static contact	$\max_N(\min(\mathcal{F}))$, $\mathcal{F}=\{f\mid\lvert Z\rvert(f)=3\,\mathrm{dB}\}$, $Z=\frac{\lVert\mathbf{F}_{\mathrm{s}}\rVert}{\lVert\mathbf{F}_{\mathrm{d}}\rVert}$	Hz	30
MVC	Material Variation Consistency	capability of the controller to successfully adapt to varying material properties without reprogramming	$\frac{n_{\mathrm{s,m}}}{N_{\mathrm{m}}}$, $n_{\mathrm{s,m}}=\sum_{i=1}^{N_{\mathrm{m}}}u\left(\frac{1}{N}\sum_{i=1}^{N}(N_{\mathrm{s}})\right)$, $N_{\mathrm{s}}=u(\Delta F^{+})\,u(\Delta F^{-})-1$, $\Delta F^{+}=\lVert\mathbf{F}_{\mathrm{d}^{+}}\rVert-\lVert\bar{\mathbf{F}}\rVert$, $\Delta F^{-}=\lVert\bar{\mathbf{F}}\rVert-\lVert\mathbf{F}_{\mathrm{d}^{-}}\rVert$	%	100
IS	Impact Stability	capability of the controller to successfully control forces after dynamic contact at $250\,\mathrm{mm/s}$	$\frac{n_{\mathrm{s,i}}}{N_{\mathrm{i}}}$, $n_{\mathrm{s,i}}=\sum_{i=1}^{N_{\mathrm{i}}}(N_{\mathrm{s}})$, $N_{\mathrm{s}}=u(\Delta F^{+})\,u(\Delta F^{-})-1$, $\Delta F^{+}=\lVert\mathbf{F}_{\mathrm{d}^{+}}\rVert-\lVert\bar{\mathbf{F}}\rVert$, $\Delta F^{-}=\lVert\bar{\mathbf{F}}\rVert-\lVert\mathbf{F}_{\mathrm{d}^{-}}\rVert$	%	100

Reference system:

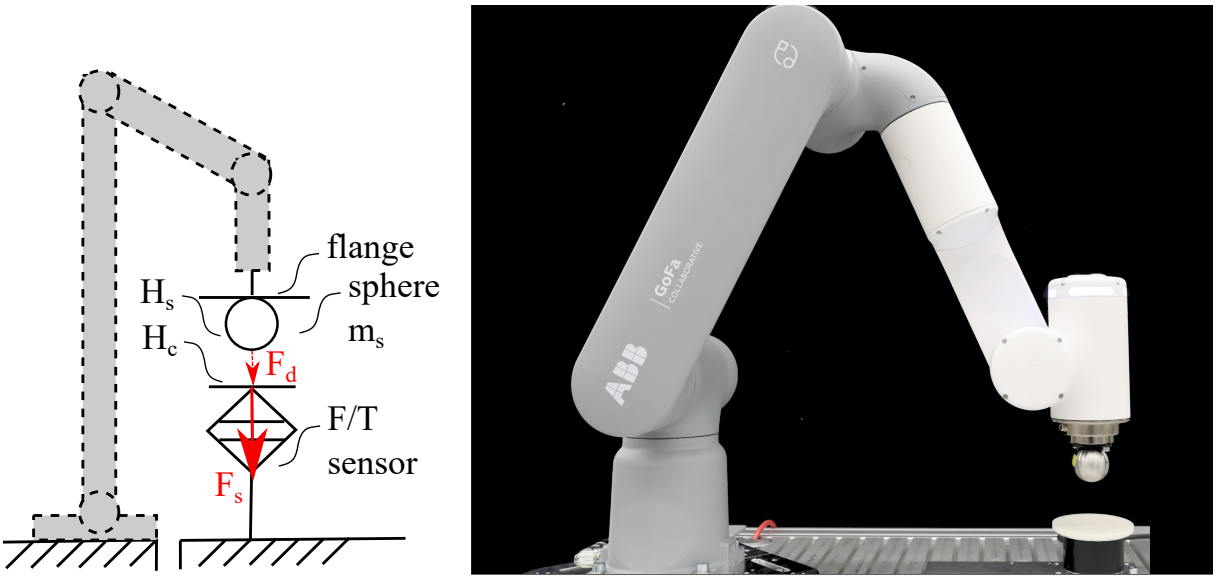

Figure 4: Reference system for controller force metrics.

Table 6: Setup definitions

component	considered quantity	value	accuracy req.
sphere	material	stainless steel	
	mass m_S [kg]	0.2	$\pm$ 0.005
	hardness H_S [HB]	250	
	radius r_S [mm]	25	
force sensor	sampling frequency f [Hz]	300	
	measurement range ΔF [N]	500	
cover 2	material	high-density Poly-Ethylen (PE-HD)	
	hardness H_C [ShD]	$\approx$ 63-67	
robot	desired force [N]	$\mathbf{F}_d = [0, 0, 8]$ N	1

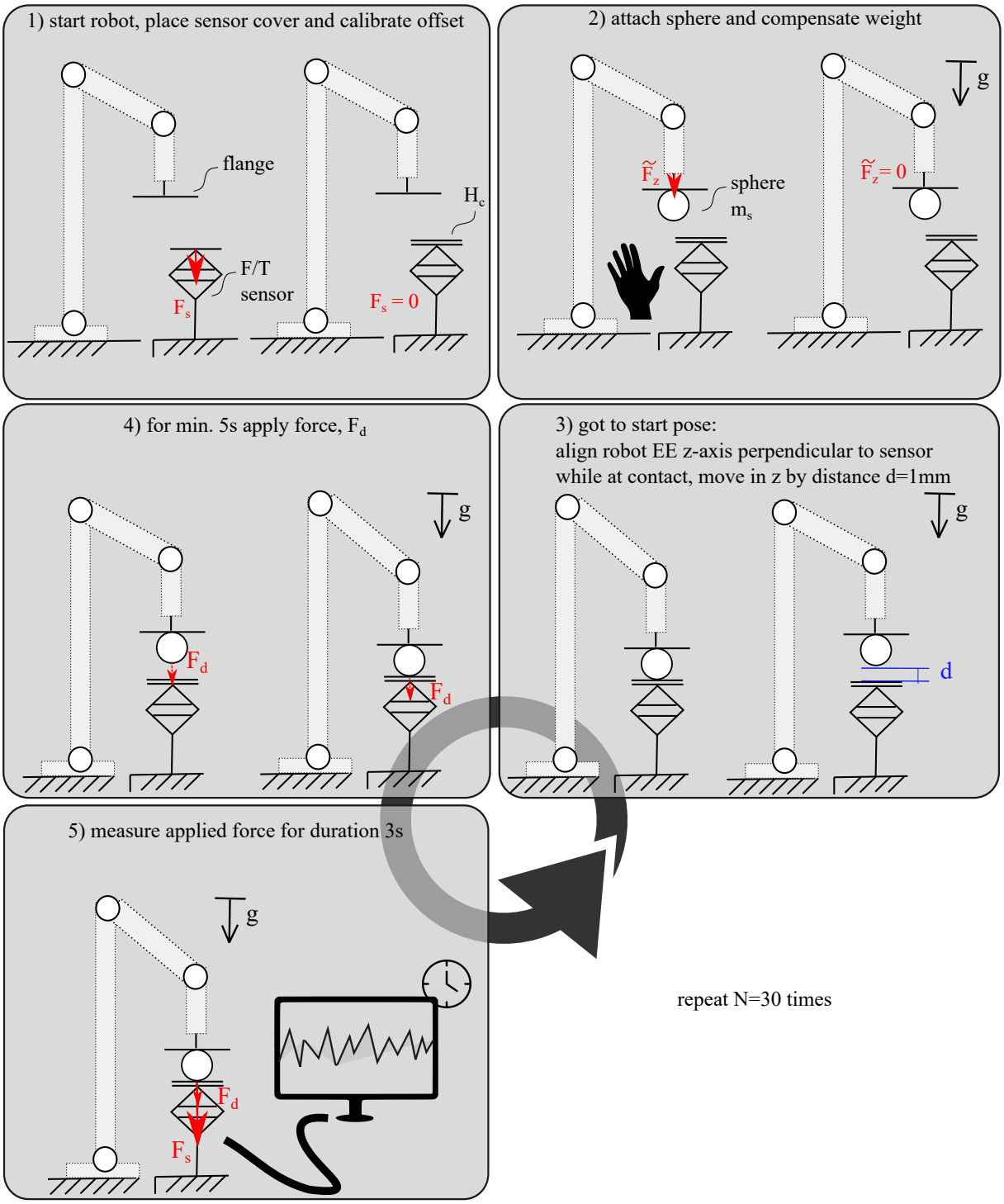

Figure 5: Measurement Procedure for A_{cF}, P_{cF}, and RS_{cF}.

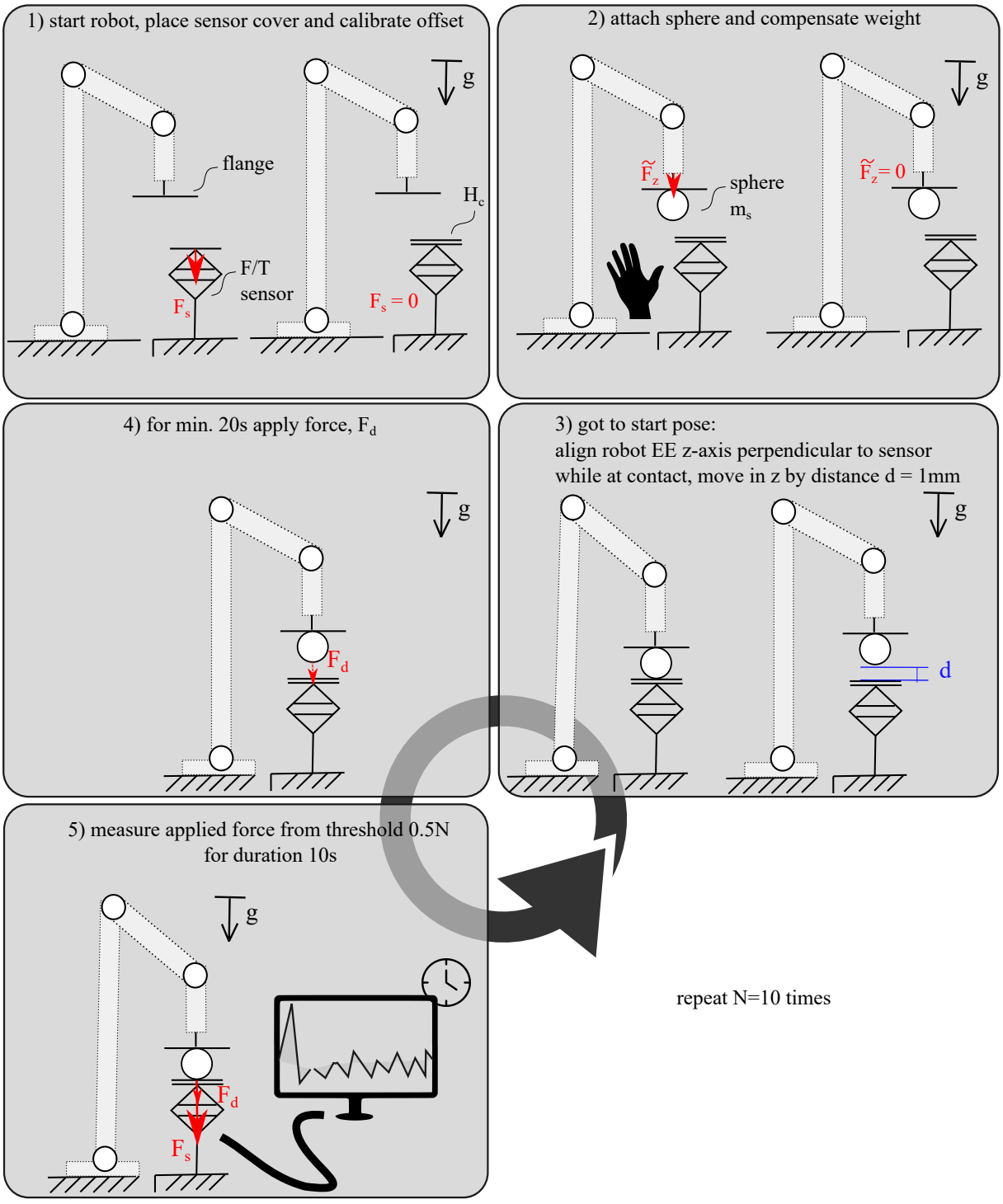

Figure 6: Measurement Procedure for OV and TS.

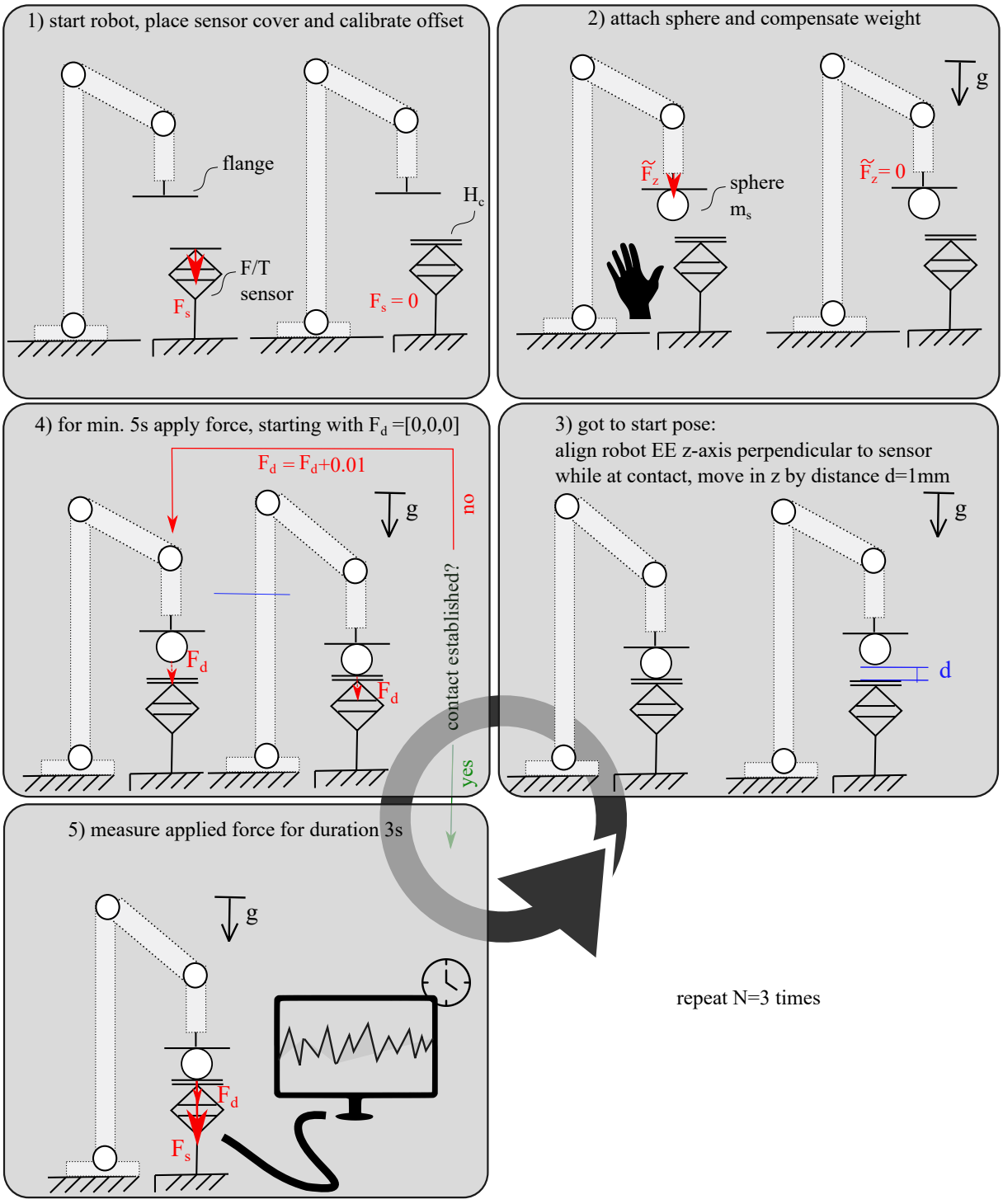

Figure 7: Measurement Procedure for MAF.

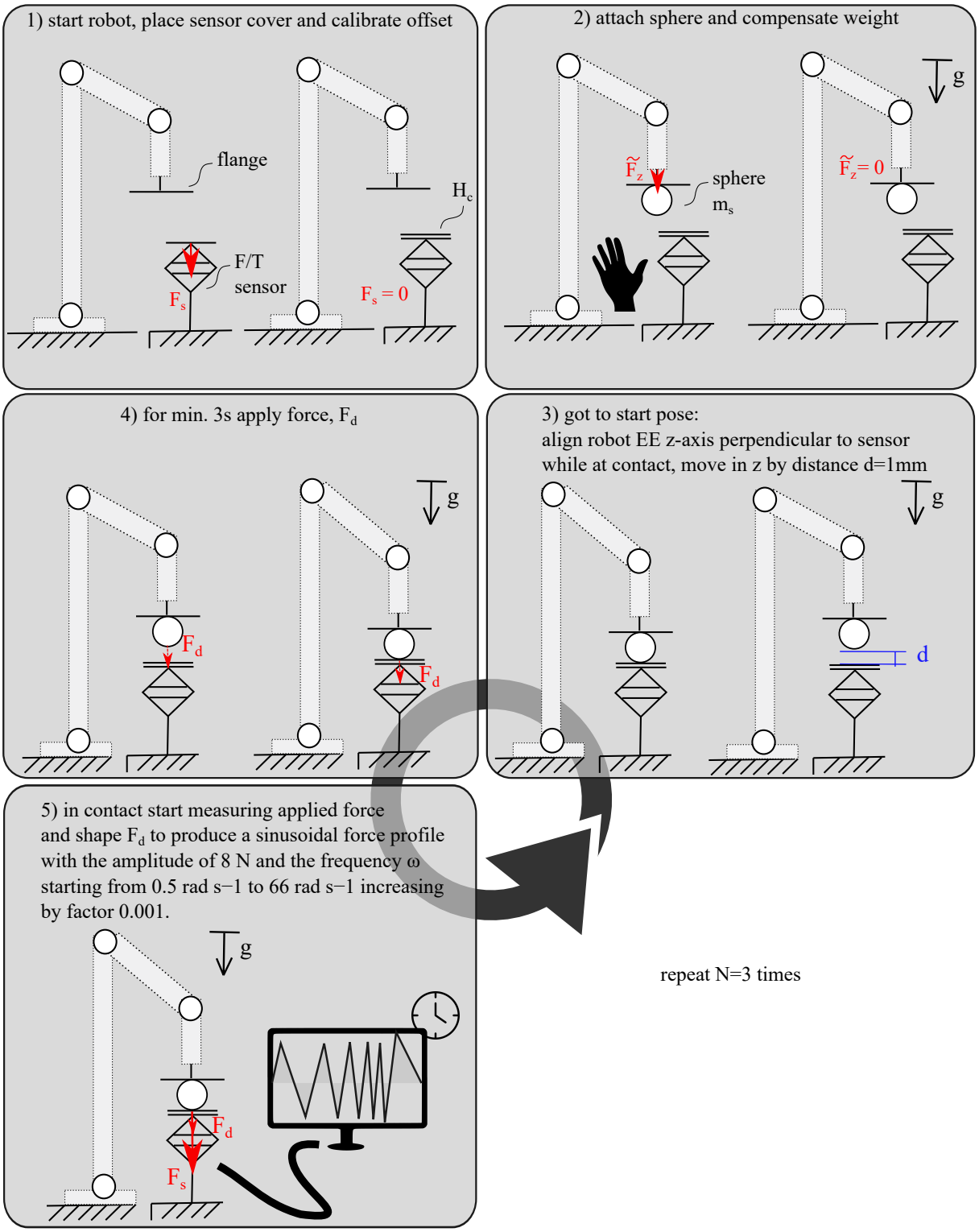

Figure 8: Measurement Procedure for B_c.

14 **Material Variation Consistency and Impact Stability:**

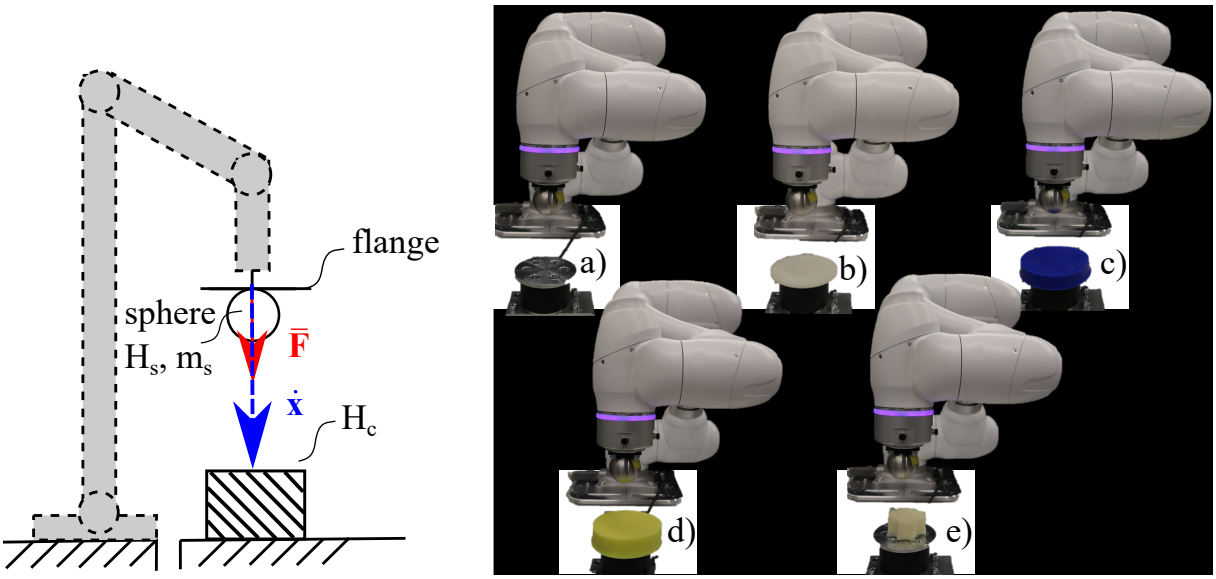

Figure 9: Reference system for the material variation consistency and impact stability.

Table 7: Setup definitions

component	considered quantity	value	accuracy req.
sphere	material	stainless steel	
	mass m_{S} [kg]	0.2	$\pm\, 0.005$
	hardness H_{S} [HB]	250	
	radius r_{S} [mm]	25	
cover 1	material	aluminum alloy EN AW-7021	
	hardness H_{C} [HB]	$\approx$ 110-120	
cover 2	material	high-density Poly-Ethylen (PE-HD)	
	hardness H_{C} [ShD]	$\approx$ 63-67	
cover 3	material	rubber	
	hardness H_{C} [ShA]	≈ 50	
cover 4	material	rubber	
	hardness H_{C} [ShA]	≈ 10	
cover 5	material	foam	
	hardness H_{C} [ShA]	$<< 10$	
robot	desired force [N]	$\mathbf{F}_{\mathrm{d}} = [0, 0, 8]\,\mathrm{N}$	1
	force measurement [N]	available	0.1
velocity sensor	type	photointerruptor (light barrier)	
	velocity (v_{c}) measurement [m/s]		0.001
end-effector (for v_{c} measurement)	thickness [mm]	10	$\pm$ 0.02
desired contact velocities v_{c}	velocity [mm]	0.05	$\pm$ 0.005
		0.25	$\pm$ 0.005

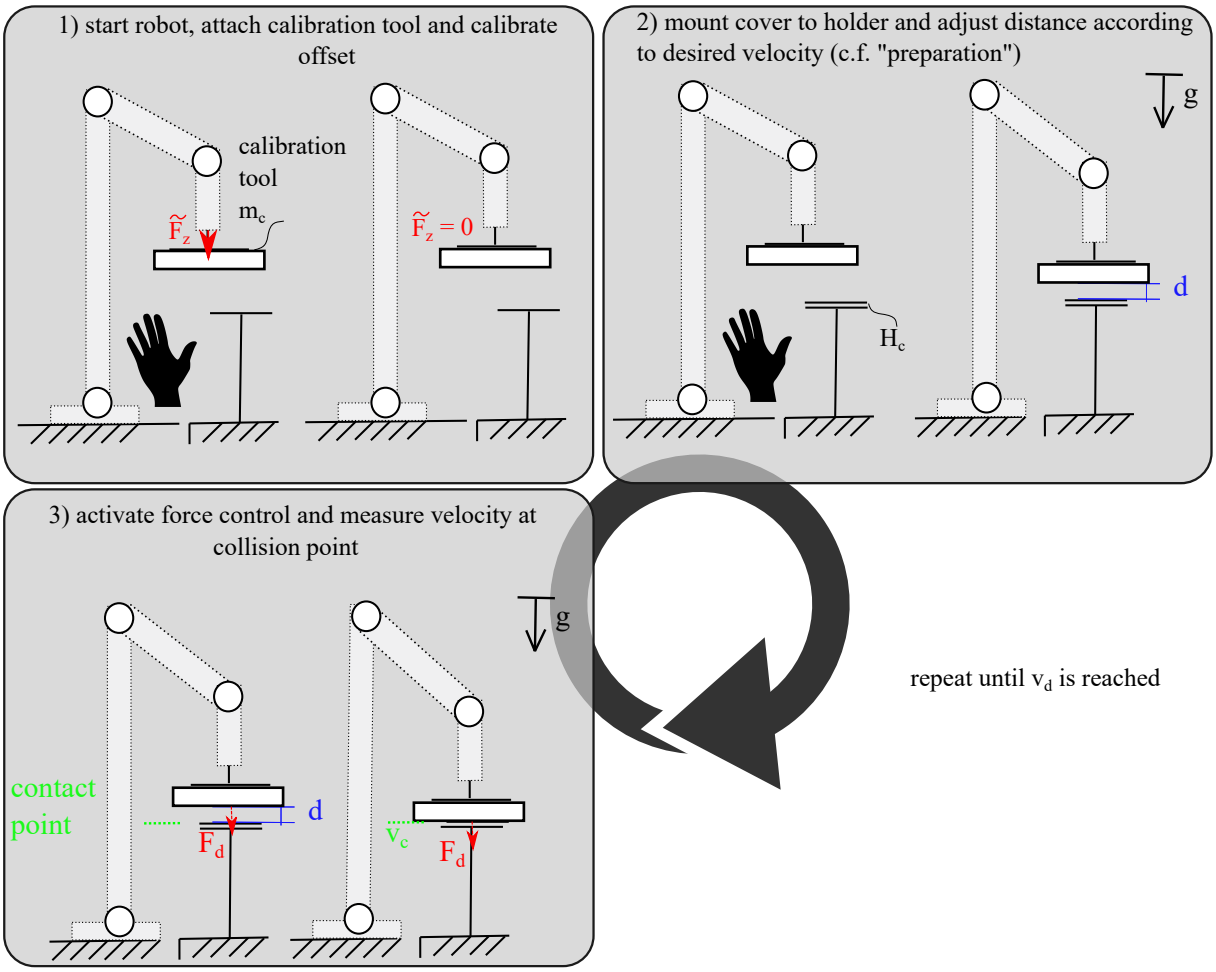

Figure 10: Preparation for Measurement Procedure for IS and MVC.

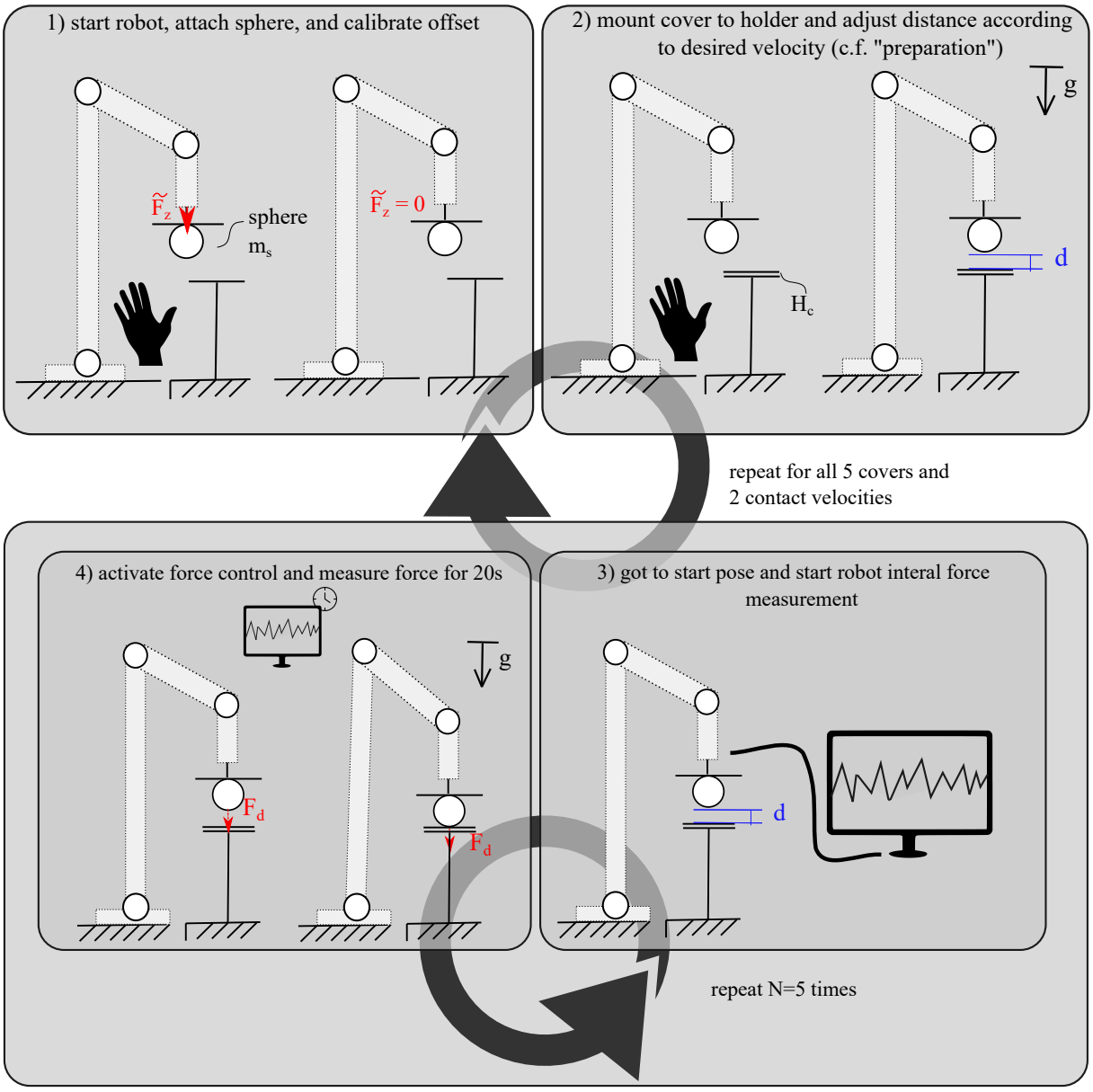

Figure 11: Measurement Procedure for IS and MVC.