Appendix A
Notation and Definitions

This works is meant to present an unified theory of cable-driven parallel robots. As part of this attempt both the terminology and the mathematical description shall be harmonized. However, due to the number of fields touched, it is a challenge to keep symbols through all chapters and to maintain common notion where possible. In the following, the systematics for notation are described.

Scalar real values and natural numbers are noted in italic letters s. Vectors are noted in bold as $\mathbf{x}$ and their symbols are usually lower case letters. Where necessary, information on the dimension of the vector is given when introducing the vector. The components of vectors and matrices are noted in square brackets as $\mathbf{r} = [x, y, z]^{\mathrm{T}}$. Position vectors, velocities, and accelerations as well as forces and torques are understood to be elements of $\mathbb{R}^3$ for spatial robots and $\mathbb{R}^2$ for planar robots. If not stated otherwise, vectors are understood to be columns. The zero vector with all elements vanishing is denoted by $\mathbf{0} \in \mathbb{R}^n$ and its dimension n shall be selected from the context. When comparing two vectors by using the operators $<, >, \leq, \geq$ the comparison has to be done component-wise. Let $\mathbf{a} = [a_1, \ldots, a_n]^{\mathrm{T}} \in \mathbb{R}^n$ and $\mathbf{b} = [b_1, \ldots, b_n]^{\mathrm{T}} \in \mathbb{R}^n$, then

$$\mathbf{a} > \mathbf{b} \quad \text{holds true if and only if} \quad a_i > b_i \quad \forall \quad i = 1, \ldots, n \quad . \tag{A.1}$$

Sometimes vectors are also compared with scalar values. This comparison is also understood to be executed component-wise. Let $\mathbf{a} = [a_1, \ldots, a_n]^{\mathrm{T}}$ and $s \in \mathbb{R}$, then

$$\mathbf{a} > s \quad \text{holds true if, and only if,} \quad a_i > s \quad \forall \quad i = 1, \ldots, n \quad . \tag{A.2}$$

The scalar product of two vectors $\mathbf{a} \cdot \mathbf{b}$ of the same dimension is the sum of the product of its respective components. The scalar product is equivalent to

$$\mathbf{a} \cdot \mathbf{b} = \mathbf{a}^{\mathrm{T}}\mathbf{b} = \sum_i a_i b_i \quad . \tag{A.3}$$

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The notion $\mathbf{a}^2$ is a shorthand for

$$\mathbf{a}^2 = \mathbf{a}\cdot\mathbf{a} = \mathbf{a}^\mathrm{T}\mathbf{a} = \sum_i a_i a_i = ||\mathbf{a}||_2^2 \tag{A.4}$$

and the result is a scalar which is the squared length of the vector or the square of the Euclidean norm of vector $\mathbf{a}$. Matrices are noted with bold letters as $\mathbf{M}$ and their symbols are usually capital letters. If not said otherwise, the matrices here are all real-valued. The square identify matrix $\mathbf{I} = \mathrm{diag}(1, \ldots, 1) \in \mathbb{R}^{n\times n}$ as well as the zero matrix $\mathbf{0} \in \mathbb{R}^{m\times n}$ with all elements being zero have dimensions m, n fitting to the context of the equations, respectively. A set is denoted with calligraphic letters such as $\mathcal{S}$ which also applies to the notation of the workspace $\mathcal{W}$ that is basically also a set of poses. Sets may have a finite or infinite number of elements, such as $\mathbb{R}$, $\mathbb{R}^n$, and SO_3, and we use curly brackets to enumerate elements $\mathcal{S} = \{1, 2, 5\}$. Lists $\mathcal{L}$ are special finite sets and bridge the way from mathematics to a computer implementation. In addition to mathematical sets, lists are assumed to have a well-defined sequence allowing for indexing where sets are unordered.

Interval variables are written with a hat like $\widehat{a}$. Consequently, vectors of intervals are denoted as bold letters with a hat $\widehat{\mathbf{b}}$ and interval matrices $\widehat{\mathbf{M}}$. When written in form of the lower interval bounds a and the upper bounds b, square brackets and a semicolon are used for the interval $[a; b]$. Note that this notation is used both for the application with interval analysis as well as for ordinary notation of parameter ranges.

Coordinate frames are abbreviates with a calligraphic $\mathcal{K}$, however, coordinate systems are not understood to be sets. A spatial coordinate frame is equivalent to a pose and one possible parameterization is composed from the position $\mathbf{r} \in \mathbb{R}^3$ and the orientation matrix $\mathbf{R} \in \mathrm{SO}_3 \subset \mathbb{R}^{3\times 3}$ where the special orthogonal group SO_3 is defined as follows:

$$\mathrm{SO}_3 = \left\{\mathbf{R} \in \mathbb{R}^{3\times 3} \quad | \quad \mathbf{R}\mathbf{R}^\mathrm{T} = \mathbf{I}, \quad \det(\mathbf{R}) = 1\right\} \quad . \tag{A.5}$$

Subscripts in italic letters are understood to symbolize indices taking natural numbers, e.g. to select components from vectors and sets. Sequences of subscripts represent multiple indexing, e.g. to name the components of a matrix like $\mathbf{A}_{ij}$. Subscripts in normal letters are names, multiple normal letters without comma separation also form a name, for example $\mathcal{K}_\mathrm{TCP}$ for the coordinate frame of the TCP. When names and indices are combined as subscripts, the index is separated with an additional comma, e.g. the frame $\mathcal{K}_{\mathrm{A},i}$ denotes the ith proximal anchor point frame.

Derivatives with respect to time t are noted with dots over the letter. The rule applies both for scalar and vectors. Let s be a length, then $\dot{s} = \frac{\mathrm{d}s}{\mathrm{d}t}$ is the linear velocity and $\ddot{s} = \frac{\mathrm{d}^2 s}{\mathrm{d}t^2}$ is the linear acceleration. For the position vector $\mathbf{r}$, one gets the velocity vector $\mathbf{v} = \dot{\mathbf{r}} = \frac{\mathrm{d}\mathbf{v}}{\mathrm{d}t}$ and the acceleration vector $\mathbf{a} = \dot{\mathbf{v}} = \ddot{\mathbf{r}} = \frac{\mathrm{d}^2\mathbf{r}}{\mathrm{d}t^2}$.

The usage of poses consisting of a position $\mathbf{r} \in \mathbb{R}^3$ and an orientation $\mathbf{R} \in \mathrm{SO}_3$ needs special treatment. Such a pose represents an unique state of a coordinate frame $\mathcal{K}$ in the Euclidian motion group SE_3 which is a six-dimensional manifold composed from the product $\mathbb{R}^3 \times\ \mathrm{SO}_3$. Therefore, one can represent a pose by pair of the positions $\mathbf{r}$ and $\mathbf{R}$ that we denote with $\mathbf{y} = (\mathbf{r}, \mathbf{R})$. For many computer codes it is required to choose a parameterization for $\mathbf{R}$ such as Euler angles, Bryant angles, roll-pitch-yaw, Rodriguez parameters, Quaternion, or simply the nine coefficients $[r_{11}, \ldots, r_{33}]^{\mathrm{T}}$ of the rotation matrix. The notation $(\mathbf{r}, \mathbf{R})$ is used whenever the method is independent from the parameterization used. Parameterizations are avoided where possible for the sake of generality. However, some operations cannot be carried out without choosing a certain parameterization of rotation. The pose vector $\mathbf{y}$ is written as a tuple of parameters. Note that such parameter vectors are restricted in their mathematical operations since common operations as plus and minus, have no physical meaning if the components of the vector $\mathbf{y}$ are e.g. $\mathbf{y} = [x, y, z, a, b, c]^{\mathrm{T}}$ where x, y, z are the Cartesian coordinates and a, b, c are the Euler angles then adding or subtracting two such vectors has no physical meaning.

Appendix B
Introduction to Interval Analysis

Interval Arithmetic was firstly introduced by Ramon E. Moore [410] and was originally used to propagate computation and round-off errors in numerical computations. This is achieved by determining guaranteed bounds on computations in a robust way. Beside the handling of round-off errors, interval analysis have been proven a valuable tool in many other numerical problems such as linear algebra, solving of nonlinear equations, constraint programming, and optimization. A major property of interval analysis is its ability to derive guaranteed bounds for the values of an analytic function in a given interval. This can be done even if the coefficients of the equation are subject to uncertainties as long as one can give ranges (intervals) for these coefficients. Interval algorithms were developed for a couple of numerical problems such as solving nonlinear systems of equations, enclosing the roots of polynomials, and finding all solutions of systems of inequalities. During the last decades, interval algorithms were developed for constrained global optimization [40, 196, 359]. These methods were successfully applied to problems where conventional methods were hardly able to deal with. Especially the inherent property to deal with round-off errors in a robust way and to compute strict bounds for the numerical error of the algorithms are superior to conventional computations with real values. However, there are some additional numerical costs for the interval evaluation and for certain problems interval algorithms are rigorous but rather inefficient.

An *interval* $\widehat{x}$ is an ordered pair $[a; b]$ of two real numbers

$$\widehat{x} = [a; b] = \{x \in \mathbb{R} \mid a \le x \le b\} \quad , \tag{B.1}$$

where a is called *infimum* and b is called *supremum* of $\widehat{x}$. The difference between infimum and supremum is called *width* (diameter) of the interval and the mean value is called center (middle). Thus, the following functions are defined

$$\inf \widehat{x} = a \quad , \tag{B.2}$$

$$\sup \widehat{x} = b \quad , \tag{B.3}$$

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$$\operatorname{diam}\widehat{x} = b - a \quad , \tag{B.4}$$

$$\operatorname{mid}\widehat{x} = \frac{1}{2}(a + b) \quad . \tag{B.5}$$

The set of all real valued intervals is denoted with $\mathbb{I}$. A vector of interval is called a *box*. Analogously to the arithmetics of real numbers, the elementary operations $+, -, *, /$ are declared for the set of intervals $\mathbb{I}$ as follows:

$$\widehat{x} \circ \widehat{y} = [a; b] \circ [c; d] = \{x \circ y \mid a \le x \le b, c \le y \le d\} \quad , \tag{B.6}$$

where $\circ$ is any of the elementary operations $+, -, *, /$. The following rules apply for the elementary operations

$$[a; b] + [c; d] = [a + c; b + d] \quad , \tag{B.7}$$

$$[a; b] - [c; d] = [a - d; b - c] \quad , \tag{B.8}$$

$$[a; b] * [c; d] = [\min(ac, ad, bc, bd); \max(ac, ad, bc, bd)] \quad , \tag{B.9}$$

$$[a; b] \,/\, [c; d] = [a; b] * [1/d; 1/c] \quad \text{if} \quad 0 \notin [c, d] \quad . \tag{B.10}$$

The result of any such operation is an interval, i.e. the set of intervals is closed with respect to the arithmetic operations $+, -, *$. Only for the division, the expression $\widehat{x}/\widehat{y}$ is undefined if $0 \in \widehat{y}$.[1] The degenerated intervals of the form $[a; a]$ are associated with the real numbers and the interval operations yield the same results. Furthermore, the interval operations converge towards the results for real values arithmetics, if the width of all intervals converges towards zero. Therefore, interval analysis can be understood as a generalization of the arithmetics of real numbers [410].

An interval is called *positive* (*negative*) if $\inf \widehat{x} \ge 0$ ($\sup \widehat{x} \le 0$) and *strictly positive* (*strictly negative*) if $\inf \widehat{x} > 0$ ($\sup \widehat{x} < 0$). Two intervals $\widehat{x}, \widehat{y}$ are *equal* if $\inf \widehat{x} = \inf \widehat{y}$ and $\sup \widehat{x} = \sup \widehat{y}$. Intervals are partially sorted and $[a; b] < [c; d]$ holds true only if $b < c$.

B.1 Interval Evaluation of a Function

Interval analysis can be applied to ordinary continuous[2] functions that are composed of the elementary operations as introduced in the previous section. This is achieved by exchanging the real-values variables $(x_1, \ldots, x_n)$ of the function $f : \mathbb{R}^n \to \mathbb{R}$

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[1] It is possible to extended interval arithmetics with the values $\pm\infty$ as limits of an interval where the division by 0 is allowed. Such an extended interval arithmetics is also closed with respect to division, see [196].

[2] We restrict ourselves to continuous functions because it serves well for the purpose of this work. Anyway, there are extended techniques that allow to deal with non-continuous functions as well, see e.g. [196].

by real-values intervals $(\widehat{x}_1, \ldots, \widehat{x}_n)$. This results in a function $f^{\mathrm{I}} : \mathbb{I}^n \rightarrow \mathbb{I}$ that maps the interval vector $\widehat{x}$ onto an interval $\widehat{y}$. Since the interval function f^{I} is equal to the real-valued function f except for the type of its arguments, we omit a special notation for such interval functions. We assume that interval operations have to be applied for evaluation if at least one operand is in an interval. Calculating the interval value of a function is called *interval evaluation* of the function. From the definition of the interval operations, it follows

$$\widehat{z} = f(\widehat{\mathbf{x}}) \quad \Leftrightarrow \quad \inf \widehat{z} \leq f(\mathbf{x}) \leq \sup \widehat{z} \quad \forall\, \mathbf{x} \in \widehat{\mathbf{x}} \quad , \tag{B.11}$$

i.e. the interval evaluation of a function yields guaranteed bounds $\widehat{\mathbf{z}}$ of the image space of the function f over the interval box $\widehat{\mathbf{x}}$.

B.2 Over-Estimation

Beside many similarities between interval arithmetics and arithmetics of real numbers, there are some important differences that needs to be taken into account. Both commutative and associative property holds true for addition and multiplication of intervals. Contrary, the distributive property cannot be used with intervals in its common form

$$\widehat{a}(\widehat{b} + \widehat{c}) \neq \widehat{ab} + \widehat{ac}, \quad \widehat{a}, \widehat{b}, \widehat{c} \in \mathbb{I} \quad . \tag{B.12}$$

Sub-distributivity is a weak form of the distributive property and it holds true for every interval $\widehat{a}, \widehat{b}, \widehat{c} \in \mathbb{I}$

$$\widehat{a}(\widehat{b} + \widehat{c}) \subset \widehat{ab} + \widehat{ac} \quad . \tag{B.13}$$

To receive an interval evaluation with as strict as possible bounds, it is favorable to evaluate the left hand side of Eq. (B.13) since it yields stricter bounds. In general, it can be stated that an interval evaluation yields closer bounds if every variable occurs only once in the function. If the same variable occurs multiple times in the same function, the so-called *interval identity* is lost, i.e. it cannot be taken into account that each instance of the variable x has the same value $x \in \widehat{x}$. Therefore, we may receive an over-estimation for the function's image if interval identity is not fulfilled. Even for very simple expressions such as $\widehat{a}^2 \subset \widehat{a} * \widehat{a}$ and $0 \subset \widehat{a} - \widehat{a} \neq 0$, we find a significant over-estimation. For example, evaluating the former expressions for $\widehat{x} = [-1; 1]$ yields $\widehat{x} * \widehat{x} = [-1; 1]$ where the strict result is $\widehat{x}^2 = [0; 1]$. The source of the overestimation comes from dealing with $\widehat{x} * \widehat{x}$ as with $\widehat{x} * \widehat{y}$, where the ranges for $\widehat{y} = \widehat{x}$ are identical just by chance. Functions with complicated expressions cannot be factored or rearranged so that every variable occurs only once. Therefore, over-estimation cannot be avoided in general. But still one can often find equivalence transformations leading to a smaller over-estimation. On the other hand, if interval identity holds true, one can conclude from the evaluation of the function

$$\widehat{y} = f(\widehat{\mathbf{x}}) \tag{B.14}$$

that f is surjective in the interval $\widehat{y}$, i.e. for every value $y \in \widehat{y}$ in the image space it exists at least one $\mathbf{x} \in \widehat{\mathbf{x}}$ in the domain.

B.3 Software and Implementation

The inclusion of a value in an interval is mathematically justified under the assumption that any number can be exactly represented with round-off errors. In practice, this is hardly possible due to finite accuracy of real computer hardware. Since the number of digits in limited at least by the amount of memory, we have to deal with some kind of round-off errors in any computation. Most microcomputers allow to control the direction of the round-off effect so that one receives a range of values where the exact value is enclosed. A systematic control called outward round-off is supported by many computers and allows to enclose the real value in an interval. An important application to interval analysis is therefore to keep track of all round-off errors during a computation. These errors can be a consequence of uncertainties in the initial data as well as method errors caused by the algorithm. These round-off errors cannot be avoided by interval analysis but unlike standard real-valued computations we get a rigorous estimation of these errors. Therefore, the result of an interval computation might be an interval with an inadequate large width and thus little practical use. In any case, standard algorithms would have reported one single but completely wrong value without any indication of a catastrophic round-off effect. Due to their special ability to deal with round-off and method errors interval analysis is called *robust* or *reliable* computation and a whole branch of numerical mathematics was developed around this property.

There are a number of computer libraries and development environments for interval analysis. Results presented in this work mostly used BIAS/Profil by Knüppel [249, 250], since this library is platform-independent and work both with Windows and Linux. Other implementations such as PASCAL-XSC [194], C-XSC [248] and Sun Forte [447] offer similar functions. An extension for MATLAB (MathWorks Inc.) for interval analysis was developed by Rump [427, 428]. A notable collection of algorithms for interval linear algebra called VERSOFT is available from Rohn.

Based on basic implementation for interval arithmetics, different tools were developed to do practical interval computations with advanced algorithms. An example with many applications in mechanism science is ALIAS [101] and its extension ALIAS/Maple [102] with an interface for the computer algebra system Maple (Waterloo Maple Inc.). The basics of the interval algorithms implemented there can be found in Moore [410], Neumaier [359] and Hansen [195, 196].

A typical library for a high level computer language such as C, C++, or Python as well for the scripting languages of numerical packages provides amongst the basic arithmetics operations $+, -, *, /$ a selection of elementary functions such as $\sin(\cdot)$, $\cos(\cdot)$, $\sqrt{\cdot}$, etc. These functions are efficiently implemented from their real-valued counterparts by making use of the individual properties such as monotony in order to compute largely improved bounds. Some packages additionally include hardware-based control of round-off errors through directed rounding. Briefly speaking, this instructs the computer to conservatively select the bounds for the result of an arithmetic operation.

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