Errata: Robot Modeling and Control

Mark W. Spong, Seth Hutchinson, and M. Vidyasagar

December 13, 2015

Compiled by Katherine J. Kuchenbecker and others affiliated with MEAM 520 at the University of Pennsylvania, expanding on the errata from Seth Hutchinson.

Chapter 1

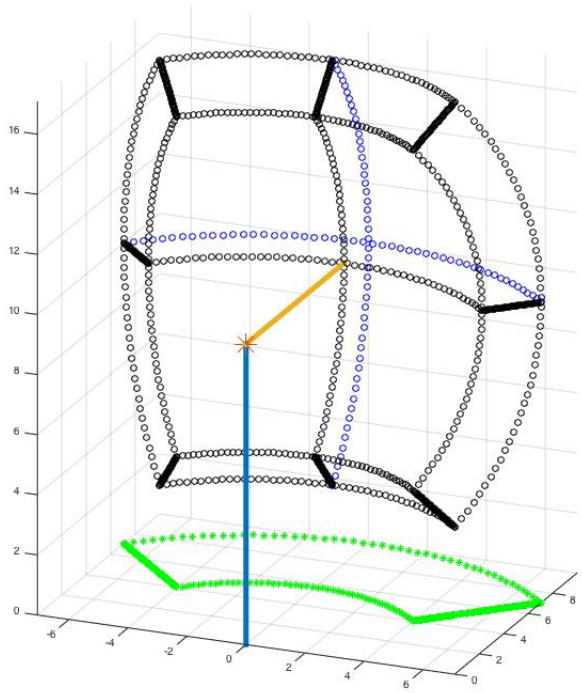
Page 13 Figure 1.10 does not show an accurate drawing of the workspace of the elbow (articulated) manipulator. The outer edge of the top view should be a circular arc segment, and the boundaries of the side view should be much more precisely drawn as well. This looks like an artist's interpretation rather than a precise workspace diagram.

Errata continue on the next page.

Page 18

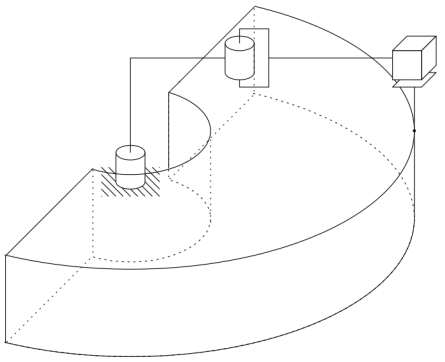
In Figure 1.17(a) the workspace is drawn incorrectly. A correct MATLAB plot of the robot with rotational joint limits being $(-\frac{\pi}{4}, \frac{\pi}{4})$ is shown below. The cyan vertical line is link 1, the yellow horizontal line is links 2 and 3, since they physically form a straight line. The big red star, where links 1 and 2 intersect, is the origin of frame 2, following DH conventions. The black and blue lines and arcs outline the workspace in 3D, and the green region shows the shadow of such a workspace. The two arcs in blue are located at the back of the workspace.

The flat surfaces at the boudaries of the workspace should not be horizontal or vertical in the usual world frame; instead they should be on planes that go through the origin of frame 2. Also you could notice that every pair (4 pairs are drawn in this plot) of the straight boundaries intersect at the origin of frame 2.



Page 18

In Figure 1.17(b) the workspace for the SCARA robot is too far away from the base. The tip of the robot should be at the far arc of the workspace. The two end arcs should also be tangent to the outer arc and should have a radius equal to the length of the robot's forearm. Generally this is a poor illustration of the workspace of a SCARA robot. Here is a version that has the workspace in the right location, but it erroneously shows straight instead of curved edges:



Page 29 In the caption for Figure 1.25, change Problem 1-15 to Problem 1-13.

Chapter 2

Page 38 At the top of the page, the vectors v_1^1 and v_2^2 should be v_1^0 and v_2^1, respectively, because Figure 2.1 shows only coordinate frames 0 and 1, without a frame 2.

Page 43 The vectors x_1, x_2, x_3 should be x_1^0, x_2^0, x_3^0, respectively.

Page 49 In the paragraph immediately before Example 2.5, change "We first rotate the frame $o_2x_2y_2z_2$" to "We first rotate the frame $o_1x_1y_1z_1$."

Page 50 In Equation (2.18) the (1,2) element of the matrix $R_{z,\theta}$ should be $-s_\theta$.

Page 56 In Equation (2.36), the (2,1) element of the matrix should be $-s_{\phi-\psi}$

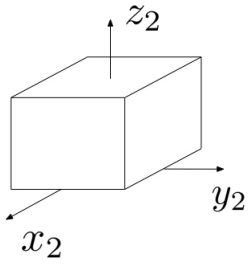
Page 61 In Equation (2.58), d_1^2 should be d_2^1. This mistake appears twice in this equation.

Page 62 In Equation (2.67) the (3,2) element of the matrix H_1^0 should be s_z.

Page 70 Question 2-38 should say "Show that $H_2^0 = H_1^0 H_2^1$."

Page 70 Question 2-39 should say "with frame $o_2x_2y_2z_2$ established at the center of the cube's bottom surface as shown."

Page 71 In Figure 2.14, frame 2 should be drawn in the following way, so that the three axes x_2, y_2, and z_2 coincide at the origin.



Chapter 3

Page 79 Equation (3.13) should begin $R_1^0 = R_{z,\theta}\, R_{x,\alpha}$ instead of having both rotations be around x. The provided elements of the matrix are correct, though.

Page 81 The line "(i) if joint i+1 is revolute, z_i is the axis of revolution of joint i+1" should be replaced by "(i) if joint i+1 is revolute, z_i is the axis of rotation of joint i+1".

Page 81-82 The textbook presents 3 cases for the relation between z_{i-1} and z_i (i) not coplanar, (ii) intersecting and (iii) parallel on page 81 and then on the following page presents elaborations of each case in another order (i) not coplanar, (ii) parallel and (iii) intersecting.

Page 82 In the fourth line from the top, "If z_{i-l} and z_i are not coplanar ..." the first subscript should be "If z_{i-1} ..."

Page 82 In section (iii), "The most natural choice..." should be "The only choice..." Delete the sentence "However, any convenient point along the axis z_i suffices."

Page 86 In the first line, "... could just as well be placed at joint 2" should read "... could just as well be placed at joint 1."

Page 87 In Figure 3.8, joint 5 is shown at $\theta_5 = -90°$. The end part of the wrist should be straight up to match the given DH parameters. The wrist is drawn correctly later in the chapter.

Page 87 The (3,2) element of A_5 should be +1.

Page 87 In figure 3.8, x_3 is not defined. It is most likely parallel to x_4.

Page 90 The x_0 axis is not labeled in Figure 3.10.

Page 90 In Figure 3.10, the origin of frame 6 should be at the end of the gripper, not at the center of the spherical wrist. This placement follows the guidelines for choosing the end-effector frame. If you leave the sixth frame where it is, d_6 should be equal to zero in Table 3.4.

Page 90 The (3,2) element in A_5 should be +1 not −1.

Page 91 In Table 3.4, d_1 should be non-zero; it is the distance from O_0 to the intersection of the z_0 and x_1 axes.

Page 91 In the expressions for r_{11}, the term $-d_2$ should be $-s_1$.

Page 91 d_x should not have a double +.

Page 91 r_{22} should have s_1 not $-s_1$.

Page 92 In Figure 3.11, Frame $x_0y_0z_0$ should be drawn at the shoulder joint of the robot arm, moved up along z_0 to match the given DH parameters in Table 3.5. Alternatively, you can add d_1 as a constant parameter in the first step of the DH transformations and adjust the matrices A_1, T_4^0.

Page 96 Should clarify the phrase "Often o_3 will also be at o_c...“; this is not often true outside of manipulators with six joints. Instead "Sometimes o_3 will also be at o_c...“ may be more clear.

Page 99 In Figure 3.14, θ_1 should be θ_1.

Page 105 Equation (3.49) should be $\theta_2 = \pi - atan2(\frac{s}{r}) = atan2(\frac{r}{s}) + \frac{\pi}{2}$.

Page 108 In Equations (3.65) and (3.66), d should be 0, since the elbow manipulator in Figure 3.13 has no shoulder offset.

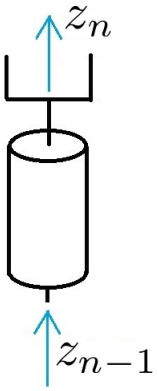
Page 108 In Equation (3.68) only the positive solution should be considered as θ_4 and θ_6 are defined here only for the positive solution for θ_5.

Page 109 In Equation (3.70), T_4^1 should be T_4^0.

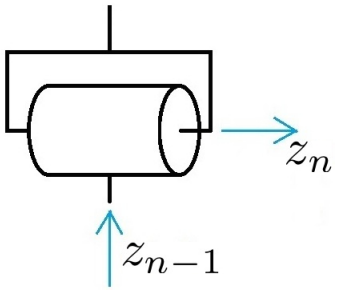
Page 109 In Equation (3.75), $\sqrt{1-c_2}$ should be $\sqrt{1-c_2^2}$.

Page 109 Equation (3.78) should read $d_3 = -o_z - d_4$.

Page 110 In step 6, it assumes z_n is parallel to z_{n-1}, given the n^{th} joint is revolute:



However, the following could also be the case when the n^{th} joint is revolute. In this configuration, $x_n = a$ (approach direction):



Chapter 4

Page 123 In the line above the equation (4.9), the "that“ in the phrase "To show this, we use **that** fact...“ should be replaced with the word "the“.

Page 130 In Equation (4.46), the summation $\sum_{i-1}^{n}$ should be $\sum_{i=1}^{n}$.

Page 132 The first line should say "the translational velocity is $\dot{d}_i$" instead of "the magnitude of the translation is $\dot{d}_i$."

Page 135 In the second sentence, the reference to Equation (4.62) should be Equation (4.63).

Page 137 In equation (4.73), the second row of o_4 should be $a_1 s_1 + a_2 s_{12}$ not $a_1 s_2 + a_2 s_{12}$.

Page 140 In the sentence before Equation (4.85), $R = R_{z,\psi} R_{y,\theta} R_{z,\phi}$ should be $R = R_{z,\phi} R_{y,\theta} R_{z,\psi}$.

Page 141 In the second line after Equation (4.90), "that the all possible" should be "that all possible".

Page 143 The textbook mentions that $o_3 = o_4 = o_5 = o_6 = o$ before (4.94), but o_3 does not need to be at the wrist center. The cross product of z_3 cross the position of the wrist center relative to o_3 will always be zero because the wrist center must lie along z_3.

Page 144 In the middle of the first paragraph, θ_4 should be θ_5.

Page 144 In the middle of the first paragraph, "the are unavoidable" should be "they are unavoidable".

Page 144 In Equation (4.99) the sign of the determinant should be switched.

Page 153 In Equation (4.121), $\xi^T (JJ^T)^1 \xi^T$ should be $\xi^T (JJ^T)^{-1} \xi$.

Page 154 After Equation (4.124), $\lambda_1 \geq \lambda_2 \ldots \leq \lambda_m$ should be $\lambda_1 \geq \lambda_2 \ldots \geq \lambda_m$.

Page 158 In problem 4-7, $\phi = \frac{\phi}{2}$ should be $\phi = \frac{\pi}{2}$.

Page 159 In problem 4-10, the word "acts" should be "facts".

Page 159 In problem 4-13, $R = R_{z,\psi} R_{y,\theta} R_{z,\phi}$ should be $R = R_{z,\phi} R_{y,\theta} R_{z,\psi}$.

Chapter 5

Page 170 In Equation (5.2), ζ should be ζ_i.

Page 170 In the paragraph under Equation (5.2),"attractve" should be "attractive".

Page 170 Clarification for **conic well potential** and **parabolic well potential** fields.
For **conic well potential**,

$$U_{att,i}(q) = ||o_i(q) - o_i(q_f)||$$

$$F_{att,i}(q) = \begin{cases} 1, & o_i(q) \neq o_i(q_f) \\ 0, & o_i(q) = o_i(q_f) \end{cases}$$

For **parabolic well potential**,

$$U_{att,i}(q) = \frac{1}{2}\zeta_i ||o_i(q) - o_i(q_f)||^2$$
$$F_{att,i}(q) = -\nabla U_{att,i}(q) = -\zeta_i \left(o_i(q) - o_i(q_f)\right)$$

In Equation (5.4), when $||o_i(q) - o_i(q_f)|| = d$, the two 'segments' of the attractive force evaluate to the same value,

$$-\zeta_i \left(o_i(q) - o_i(q_f)\right) = -d\zeta_i \frac{(o_i(q) - o_i(q_f))}{||o_i(q) - o_i(q_f)||}$$

This means that at the boundary $||o_i(q) - o_i(q_f)|| = d$, the gradient is well defined.

Page 175 After Equation (5.8), "inlcudes" should be "includes".

Page 177 In the first equation, the term $(a_x \sin\theta a_y \cos\theta)$ should be $(a_x \sin\theta + a_y \cos\theta)$.

Page 178 In Example 5.7, the word "repuslive" should be "repulsive".

Page 187 In the next-to-last paragraph, "near by" should be "nearby".

Page 193 The first line of text should say "The constraints $q(0) = q_0$ and $\dot{q}(0) = 0$ imply that".

Page 195 In Minimum Time Trajectories, the value of α could be negative. Consider when $q_f < q_0$; in the first part of the motion the joint accelerates in the negative direction, having acceleration of $+\alpha$ which is less than zero. After t_s, the joint decelerates, having acceleration of $-\alpha$, which is greater than zero.

Page 197 In Equation (5.28), $q(t_0)$ should be $q(t)$.

Page 198 Example 5.11 should be called "Quintic Spline Trajectory with Blending Constraints".

Chapter 6

Page 208 In Figure 6.5, the load torque τ_l is in the wrong direction. The arrowhead should be in the opposite direction, so that τ_l and τ_m act in opposite directions (through the gear ratio).

Chapter 7

Page 242 In Figure 7.2, the motor inertia should be labeled J_m and the link inertia should be labeled J_ℓ.

Page 244 The variable l is used for two different purposes: the length of the wire in Equation (7.12) and the number of holonomic constraints in Equation (7.13). These are two different variables.

Page 255 In Equation (7.53), add the term $\frac{1}{2}$ before the last summation sign.

Page 257 In Equation (7.64), change $\frac{\partial d_{kj}}{\partial q_j}$ to $\frac{\partial d_{kj}}{\partial q_i}$.

Page 261 In the first line, $I_i\omega_i^2$ should be $\frac{1}{2}I_i\omega_i^2$.

Page 262 In the matrix in Equation (7.90), the (1,1) term should be $-\ell_1 \sin p_1$.

Page 265 The first vector in Equation (7.99) should be $\begin{bmatrix} \ell_2 \cos q_2 \\ \\ \ell_2 \sin q_2 \end{bmatrix}$.

Page 266 In Equation (7.102), $\omega_3 = q_1 k$ should be $\omega_3 = \dot{q}_1 k$.

Page 276 In Figure 7.12, the term $-R_i^{i+1}\tau_i$ should be $-R_{i+1}^i\tau_{i+1}$ and the term $-R_i^{i+1}f_{i+1}$ should be $-R_{i+1}^i f_{i+1}$.

Page 277 In Equations (7.145) and (7.147), the term α_i should be $I\dot{\omega}_i$.

Page 277 In the fourth line in the paragraph after Equation (7.147), "joint s" should be "joints".

Page 278 In Equation (7.153), R_{i-1}^i should be R_i^{i-1}.

Page 278 Equation (7.155) should be $a_{c,i}^{(0)} = a_{e,i-1}^{(0)} + \dot{\omega}_i^{(0)} \times r_{i,ci}^{(0)} + \omega_i^{(0)} \times (\omega_i^{(0)} \times r_{i,ci}^{(0)})$

Page 279 In the second-to-last paragraph the reference to Figure 7.9 should be to Figure 7.8.

Page 279 In Equation (7.162), $\omega_2 = (q_1 + q_2)k$ should be $\omega_2 = (\dot{q}_1 + \dot{q}_2)k$

Page 280 In Equations (7.163) and (7.164) the terms $(\ell_1 - \ell_{c1})$ and $(\ell_2 - \ell_{c2})$ should be $-(\ell_1 - \ell_{c1})$ and $-(\ell_2 - \ell_{c2})$, respectively.

Page 280 In Equation (7.166) the term $\sin q_1$ should be $-\sin q_1$.

Page 280 In Equation (7.168), the term $\alpha_{c,2}$ should be $a_{c,2}$ and R_1^2 should be R_2^1.

Page 281 In Equation (7.169), R_1^2 should be R_2^1 and $\sin \dot{q}_2$ should be $\sin q_2$.

Page 281 The vector in Equation (7.171) should have a third element equal to 0.

Page 282 All occurrences of R_1^2 should be changed to R_2^1.

Page 300 After Equation (8.45) the term $\tilde{(\cdot)} = (\cdot) - \hat{(\cdot)}$ should be changed to $\tilde{(\cdot)} - \hat{(\cdot)} - (\cdot)$.

Chapter 9

Page 330 In Equation (9.21), $K_d\tilde{+}F$ should be $K_d\tilde{x} + F$.

Page 332 In Equation (9.27), $\frac{1}{m_c}$ should be $\frac{1}{M_c}$.

Page 333 In Equation (9.33), $(\dot{x}^d - x)$ should be $(\dot{x} - \dot{x}^d)$.

Chapter 10

Page 341 In Definition 10.1, change $f : M \to T_xM$ to $f : M \to TM$ and change

$$f(x) = \begin{bmatrix} f_1(x) \\ \vdots \\ f_m(x) \end{bmatrix} \qquad \text{to} \qquad f(x) = \begin{bmatrix} f_1(x) \\ \vdots \\ f_m(x) \end{bmatrix} \in T_xM \text{ for all } x \in M$$

Page 341 In Definition 10.2 change T_x^*M to T^*M.

Page 343 In Example 10.2, the third element of the vector $f(x)$ should be changed to $x_1 + x_3^2$.

Page 352 Equation (10.49) should be $L_{ad_f^k}(g)T_1 = 0 \; k = 0, 1, \ldots, n-2$.

Page 352 Equation (10.50) should be $L_{ad_f^{n-1}}(g)T_1 \neq 0$.

Page 353 In Equation (10.56), L should be changed to ℓ.

Page 354 In Equation (10.57), L should be changed to ℓ.

Page 354 In Equation (10.62), the left side of the last two terms should be changed to $L_{ad_f^2}(g)T_1$ and $L_{ad_f^3}(g)T_1$, respectively.

Pages 355-6 All occurrences of MgL should be changed to $Mg\ell$.

Page 359 In Equation (10.83), change $\dot{x}_1$ and $\dot{x}_3$ to x_1 and x_3, respectively.

Page 359 In Equation (10.86), change $T_1(x_1)$ to $T_1(x)$ in the first equation.

Page 362 Remove the semicolon in Equation (10.100).

Page 367 After Equation (10.113), change g_2 *it follows* to g_2. *It follows.*

Page 368 In the third sentence of Definition 10.11, change $\bar{\Delta}$ *is an involutive distribution such that* to $\bar{\Delta}$ *is an involutive distribution containing* Δ *such that.*

Page 375 In Problem 10-21, change rank 3 to rank 2.

Chapter 11

Page 387 In the second paragraph, change "Likewise, if half or the pixels" to "Likewise, if half of the pixels".

Chapter 12

Page 426 In the first row vector in Equation (12.21), change the first term L_{v_z} to L_{v_x}.

Appendix A

Page 436 In the Law of Cosines, change cb^2 to b^2 to give $c^2 = a^2 + b^2 - 2ab\cos\theta$.

Appendix D

Page 452 In Equation (D.7), change $x_i x_i$ to $x_i x_j$.