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CHAPTER 12

Self-Regulating Arc and Distance-Keyed Seam Preview in a Robotic Welding Simulator

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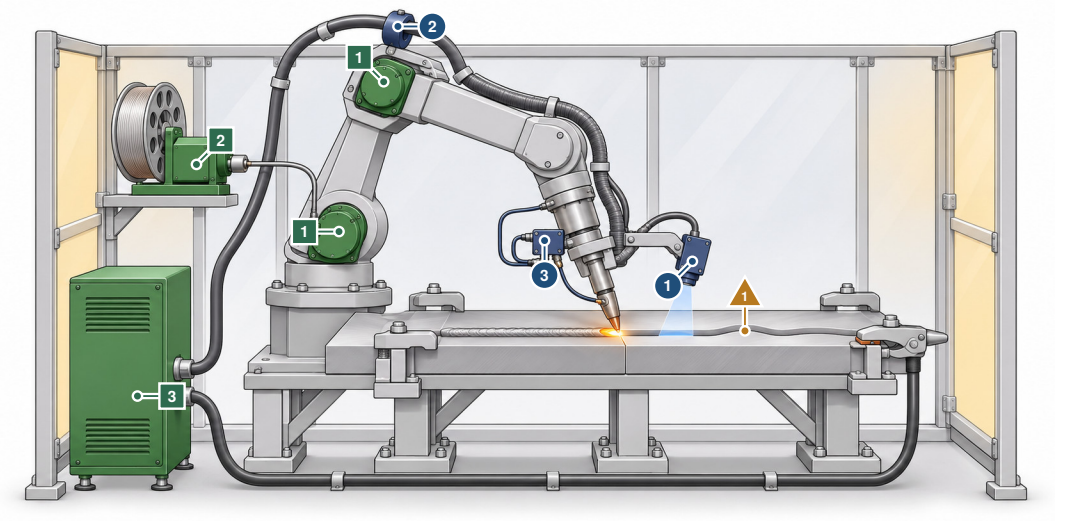
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CHAPTER 12

Self-Regulating Arc and Distance-Keyed Seam Preview in a Robotic Welding Simulator



The controller moves 1 robot axes that move the torch up and across the seam 2 wire feeder 3 power source, its voltage set with the feed

The controller reads 1 laser that reads the groove ahead of the torch 2 current sensor on the welding cable 3 voltage sensor at the torch

What disturbs it 1 a seam that bends, rises or opens ahead of the torch

Notice that the laser reads the groove ahead of the arc, so each reading belongs to a place the torch has not yet reached. Illustration, not to scale.

IN PLAIN TERMS **A Welding Arc That Sets Its Own Length**

The main idea. A robot joins two steel plates by melting a wire into the joint with an electric spark called an arc. If the torch dips closer, more current melts the wire faster, and the arc grows back to its length with no controller.

The challenge. A laser reads the joint just ahead of the torch, so each reading is saved for the moment the torch reaches that spot. A reading saved for the wrong spot steers the torch off the joint, and nothing in the reading shows it.

Why it matters. A bead that misses an edge of the joint makes a weak weld.

THREE WAYS TO READ THIS CHAPTER

Explore	11 min	the first page, the history segment (Section 12.2), the fact on the source slope (Section 12.3), the try-it segments of cases 1 and 4 (Sections 12.4 and 12.5), the fact on adaptive fill (Section 12.6) and the key points
Study	50 min	the whole chapter with its three pause points and the twelve exercises at its end
Practice	15 min	the first page, the measured cases (Section 12.6), Technology in Practice (Section 12.7), Limitations (Section 12.8) and the open challenges

The control question A constant-voltage source and a constant-speed wire feeder hold the arc length of a robotic weld with no controller between them, and a laser reads the seam a fixed distance ahead of the arc. How does the arc correct itself, what does its current reveal about the torch height, and how must a reading taken ahead of the torch be filed so that it is used at the place it describes?

Learning objectives

- Linearize the melting balance to find the time constant of arc self-regulation and the current's sensitivity to the contact-tip distance at steady state and at the weave frequency.
- Explain why a constant-current source removes the self-regulating loop and how an arc-voltage-controlled feed restores it.
- Compute the lateral error that a misconfigured look-ahead produces on a bending seam, and predict where along the bend it is largest.
- Check a travel speed and a wire feed against the fusion, undercut and underfill limits of the bead correlations.
- Configure tracking, adaptive fill and the procedure for a seam whose gap and position vary, and justify each choice by the defect it prevents.

Prerequisites Sections 1.4.3 (position loops around velocity loops), 1.4.5 and 1.4.6 (following a path and the age of a report), 1.6.2 (velocity-form PID and loop action) and 1.6.4 (running and reading a scenario).

The app https://apmonitor.com/apps/robot-arc-welding/

See also Volume 3, Chapter 6 doses a coagulant from a measured raw water turbidity, a feedforward bounded by the plant as adaptive fill is. Volume 5, Chapter 10 controls with a psychrometric soft sensor, and Volume 5, Chapter 7 follows material by volume past a delayed analyzer, as the preview buffer files readings by distance.

12.1 Introduction

A welding robot replays a path that was taught on one part, and the part in front of it is never quite that part. Robots in industrial welding operations are common, although programming them and mastering the process they carry are still far from routine [1]. In gas metal arc welding the torch feeds a consumable wire through a contact tip into an arc, a power source and a wire feeder set the process between them, and the pool that the arc leaves behind has to fuse both plates, fill the groove and freeze without a defect [2]. Successful robotic arc welding was argued early to depend on sensory feedback, with optical sensing and sensing through the arc itself as the two prevalent approaches [3]. In the simulated cell of this chapter the procedure feeds 8 m/min of 1.2 mm wire at a contact-tip-to-work distance (CTWD) of 15 mm and travels at 10 mm/s, which carries 252.1 A at 27.05 V and puts 681 J/mm into a 6 mm plate.

The plant has two properties that a block diagram hides. The first is that the arc length has no controller. A constant-voltage source and a constant-speed feeder hold it between them, because a shorter arc draws more current, more current melts the wire faster than it arrives, and the extension burns back until the arc is long again. When the plate steps up 3 mm under the torch, the model's current rises from 252.1 to 316.5 A within 17.5 ms and the arc is 90 % restored 97.0 ms after the step, while the robot's 50 Hz controller does nothing at all. A constant-current source has no such loop, and the same step leaves its arc 0.99 mm long until an arc-voltage-controlled feeder brings it back, 90 % of the way in 834.5 ms. The simulator exists to overturn one belief, that every variable a plant holds steady is held there by a controller. The 20.5 A that the constant-voltage arc keeps after the step is also a measurement, and through-the-arc sensing reads the torch height from it [3, 4].

The second property is that the laser seam sensor and the arc are separated by distance, not by time. A line scanner 40 mm ahead of the arc measures the groove's position, root gap and height, and its reading becomes useful when the torch arrives at that place, 4 s later at 10 mm/s and never if the robot stops. The controller therefore files each reading under the travel distance it describes and asks for the reading at the torch's own position. A reading filed under the wrong distance describes the wrong place. With the look-ahead configured at 20 mm on a laser mounted at 40 mm, the torch

runs up to 1.45 mm off a seam that bends 3.5 mm to either side every 300 mm, and 372 mm of the 1200 mm seam lose fusion at a groove edge.

None of this is peculiar to welding. A variable inferred from others through a model is an inferential or soft sensor, and soft sensors built from process data are a subject of their own in the process industries [5]. The psychrometric soft sensor of Volume 5, Chapter 10 is one such inference, corrected by a delayed laboratory. A controller that sees its command a fixed interval ahead is a preview controller, a class with its own optimal theory [6] and an established application in the active suspension of vehicles [7], which Volume 7, Chapter 11 treats with road-preview feedforward. The weld adds three complications to those textbook forms. Its preview lead is a distance fixed by a bracket, its part moves between the reading and the torch's arrival, and its feedforward from the measured gap runs out of room where extra metal brings more heat than the joint can take. None of the three survives the reduction of the torch to one sensor, one actuator and a delay.

The welding literature treats arc sensing, seam tracking and adaptive filling as sensor and process technology [8, 9], and a control course meets preview and inferential control as block diagrams, if at all [10], so a student rarely sees an arc correct itself faster than any controller could, or a correct laser reading used at the wrong place. This chapter shows both properties on a simulated robotic arc welding cell whose log keeps the true seam, CTWD, arc and bead apart from what the laser, the current and the voltage report. The melting-rate model, arc sensing, seam tracking, preview control and adaptive fill follow published practice. Three measured results carry the chapter: a linearization of the model's own arc that predicts the recovery time of self-regulation to within 9 % and orders it across source slopes, the rise with frequency of the current's sensitivity to the distance, which sets the calibration a weaving tracker carries, and the law by which a misconfigured look-ahead becomes a lateral error. The model has 18 states at a 0.5 ms step, with a preview buffer keyed by distance, a bead scored every millimeter, a speed guard that reports an infeasible target, and wire and deposit ledgers that close, all given in enough detail to rebuild it. Eight cases and a graded seam separate a physical loop from a controlled one, an inference from a measurement, and a reading from the place it describes.

Section 12.2 reviews how arc sensing and seam vision arose. Section 12.3 gives the circuit, the wire, the axes, the part and the bead as modeled, and Section 12.4 linearizes the arc's own loop. Section 12.5 describes the controller as built, Section 12.6 reports the eight cases and the graded seam, Section 12.7 names the devices of real welding cells, and Sections 12.8 and 12.9 state the limitations and the conclusions. The exercises of Section 12.10 run the cases in the application.

12.2 Arc Sensing, Seam Vision and the Adaptive Cell

The gas metal arc process feeds its electrode continuously, so the power source and the feeder share a single task, which is to melt the wire exactly as fast as it arrives. The process, its power sources, its monitoring and control, and its automation are treated together in one text [2], and its modeling, sensing and automatic control in another [11]. The electrode extension, the length of wire between the contact tip and the arc, is where the balance is struck. Dynamic models of the extension combine the melting rate, the temperature-dependent resistivity of the wire and the arc voltage, derived from mass continuity and energy relations for use in adaptive control [12]. A later model of the extension driven by the process voltage reproduced the frequency response of the real process, was accurate to about ± 0.6 mm against high-speed video, and was offered for through-the-arc sensing and arc length control [13]. The drops that the arc carries across have been modeled in their own right [14].

Robots came before the sensors that could guide them. A 1983 review of robotic arc welding categorized the sensor requirements by design requirements, joint imperfections, weld shape deviations and process characteristics, and covered the optical and through-the-arc approaches [3]. The history segment below follows the visually guided robot and the arc sensor that came next, and the simulated cell carries the same combination as that robot, a sensor ahead of the torch, a lateral tolerance of half a millimeter and a procedure scheduled on the gap.

Table 12.1 Variables of the Cell by Role, Initialized for Case 1

Variable	Role	Value at reset	Range
CTWD	CV of HC, true	15.00 mm SP	10–25
V_{tip}	CV of AVC (CC only)	27.01 V, SP 27.0	18–36
e_b	CV of TC, true	0 mm	y_{SP} ±3
bead flags per mm	quality, true	sound	5 defects
Δz, Δy	MVs, corrections	0 mm, 0 mm	±10
WFS_{cmd}	MV, feeder	8.0 m/min	1.5–18
V_{oc}	setting, synergic trim	31.8 V	20–42
v_{SP}	setting, travel	10 mm/s	2–20
y_{off}, a, A_b	DVs, seam	0, 0, 0 mm	±5, ±10, 0–4
g_0, profile	DV, root gap	1.0 mm, constant	0–3
z_r, z_{st}	DVs, plate height	0, 3 mm	±5, ±4
k_d	DV, thermal drift	0	0–2
spatter, window	DVs, laser	0 %, clean	0–100
gas, cast δ_c	DVs, shielding, wire	100 %, 0 mm	0–120, ±1.5
i, l_s, ϕ	states, arc	251.9 A, 10.73 mm, 0.5	—
WFS, s, v	states, feed, travel	8.0 m/min, 0, 0	—
y, $\dot{y}$, z, $\dot{z}$	states, axes	0, 0, z_p + 15 mm, 0	—
i_f, V_f	states, transmitters	251.9 A, 27.01 V	—
E_p, e_1, e_b	states, pool, bead	0, 0, 0	—
E_{arc}, L_{fed}, L_{mlt}	states, ledgers	0, 0, 0	—

Ranges in the units of the value column, a in mm per m, k_d in mm per 100 kJ, z_r over 100 to 700 mm and z_{st} at 60 mm.

HISTORY A Robot That Saw the Seam, 1985

Conventional robots of the early 1980s struggled to weld sheet steel pressings 1 to 2 mm thick. Wear of tools and fixtures, springback and thermal distortion put the torch as much as ±3.0 mm from the seam. In 1985 a model-based visual feedback system guided a metal inert gas welding robot on such parts. It detected gap width, standoff error and lateral error in lap, T and butt joints, corrected the torch to within ±0.5 mm, and used the measured seam width to change the welding parameters during the weld [15]. Sensing through the arc itself grew beside it. An arc sensor for butt joints, published in 1991, read the torch position from the welding current and overcame that signal's fluctuation by fitting it to a curve inversely proportional to the tip-to-workpiece distance [4].

Seam tracking for robotic welding has since been reviewed as a family of sensors and feature-extraction methods for the start and end of the weld, its edges, the joint width and the path [8]. Adaptive welding answers distortion, varying seam preparation and a changing gap during the weld by adjusting the travel speed and the torch orientation, and the wire feed, arc length and process dynamics through synergic settings [9]. Humping and discontinuous beads often limit the travel speed, and with it the productivity, of gas metal arc welding, and dimensionless process maps give the limiting speed as a function of the process parameters [16]. Welding distortion, which moves the joint while it is being welded, has been predicted together with the residual stress for a thin-plate butt-welded joint [17].

12.3 The Cell as Modeled

The simulated cell welds a single-V butt joint 1.2 m long in 6 mm steel plate in one pass, with 1.2 mm wire in a spray arc at the procedure of Section 12.1. The robot is reduced to three Cartesian servo axes, travel along the taught straight path and lateral and height corrections across it, and the part is where it is rather than where it was taught. The arrangement, the instruments and every symbol of the equations are shown in Figure 12.1, and Table 12.1 classifies them as controlled, manipulated, disturbance and state variables.

Eighteen states are integrated, the arc current and electrode extension, the droplet phase, the wire feed behind the feeder, the travel distance and speed, the lateral and height positions and velocities,

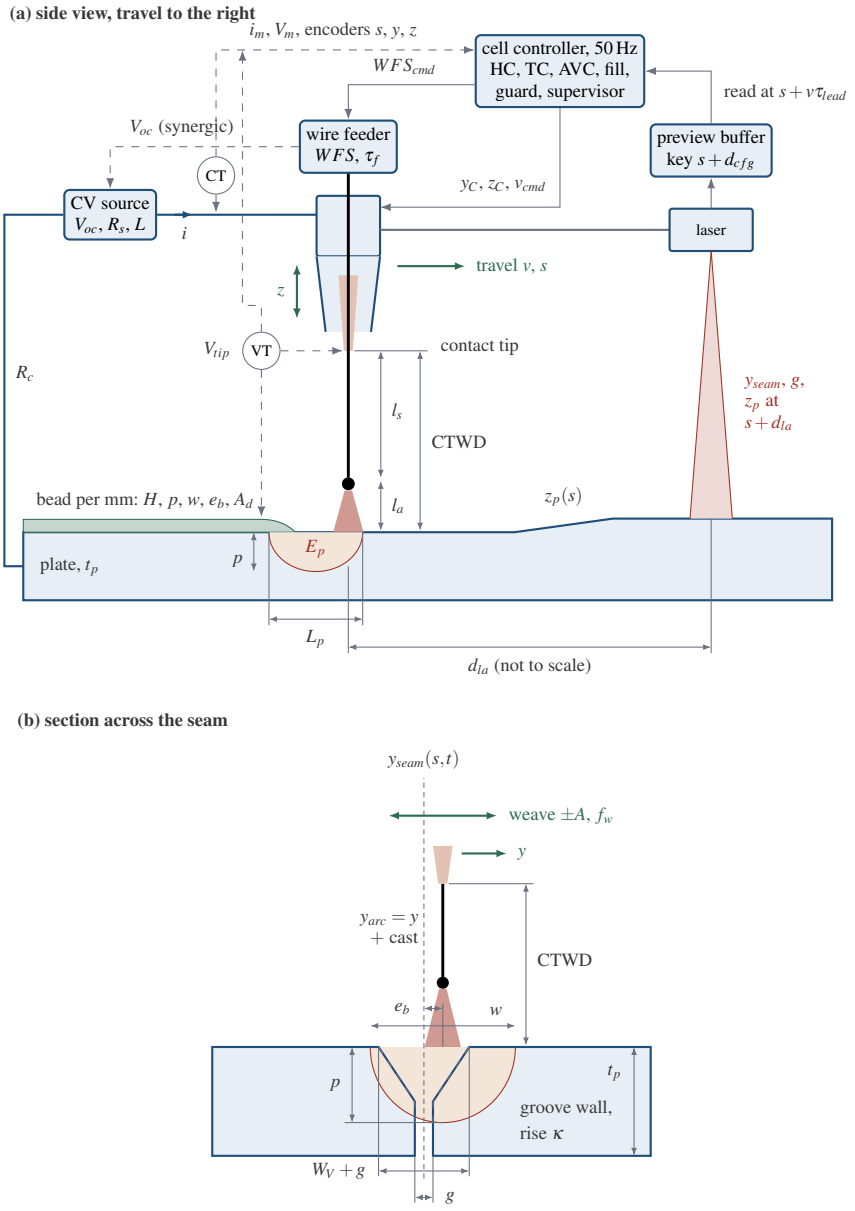


Figure 12.1 The welding cell as modeled. In (a), with travel to the right, the source (V_{oc}, R_s, L) drives i through the cable and tip (R_c), the extension l_s and the arc l_a, which span the CTWD, the feeder pushes wire at WFS behind τ_f, the pool of length L_p holds E_p and penetrates p, and the laser reads y_{seam}, g and z_p a distance d_{la} ahead for the buffer to file under $s + d_{cfg}$. CT and VT are the current and torch-voltage transmitters. In (b), drawn below (a) and across the seam at the arc, the V-groove of top width $W_V + g$ in plate of thickness t_p has walls the arc sees rising by κ per unit offset, and the bead of width w sits at $y_{seam} + e_b$. Distances in (a) are not to scale, and e_b in (b) is exaggerated.

the current and voltage transmitters, the pool energy, two stages of the bead's offset from the seam, and three ledgers of arc energy, wire fed and wire melted, all on one step and in SI units.

12.3.1 The Circuit and the Arc

The source's line, an open-circuit voltage less a slope, drives the current through an inductance, the cable and contact tip, the electrode extension and the arc, as shown in Equation (12.1).

$$\begin{aligned} L\frac{\mathrm{d}i}{\mathrm{d}t} &= V_{oc} - (R_s + R_c)\, i - V_{tip} \\ V_{tip} &= V_{arc} + r_w\, l_s\, i \\ V_{arc} &= V_0 + E_a \max(l_a - \Delta l_d,\ l_{min}) + R_a\, i \end{aligned} \tag{12.1}$$

where i is the arc current, V_{oc} the open-circuit voltage, R_s the source slope, R_c the cable and contact-tip resistance, V_{tip} the voltage a voltmeter reads between the contact tip and the work, r_w the hot resistance of the wire per unit length, V_0 the anode and cathode falls together, E_a the column gradient, l_a the arc length, Δl_d the shortening by the hanging droplet, $l_{min} = 0.1\,\mathrm{mm}$ and R_a the arc's own resistance. With the arc switched off the current decays as $\mathrm{d}i/\mathrm{d}t = -i/1\,\mathrm{ms}$. At the default 31.8 V, a slope of 1.5 V per 100 A and $L = 0.3\,\mathrm{mH}$ the arc settles at 251.9 A and 27.01 V with $l_s = 10.73\,\mathrm{mm}$, and the circuit's own time constant L/R_Σ is 6.3 ms, with $R_\Sigma = R_s + R_c + R_a + r_w l_s = 47.7\,\mathrm{m\Omega}$.

> ✦ DID YOU KNOW? **Two Volts for Every Hundred Amperes**
>
> A constant-voltage welding source is not quite constant: its voltage falls by about 2 V for each 100 A it delivers. The designer picks that slope so that a short arc gets more power and a long one less, which holds the arc length [18]. The source of this chapter falls 1.5 V per 100 A.

12.3.2 The Wire and Its Melting Rate

The feeder pushes the wire forward while the arc and the extension's own resistance melt it back, as shown in Equation (12.2).

$$\begin{aligned} \frac{\mathrm{d}l_s}{\mathrm{d}t} &= WFS - MR, \qquad MR = k_1\, i + k_2\, l_s\, i^2 \\ l_a &= CTWD - l_s \\ \tau_f \frac{\mathrm{d}WFS}{\mathrm{d}t} &= WFS_{cmd} - WFS \end{aligned} \tag{12.2}$$

where MR is the melting rate in length of wire per second while the arc burns, the first term is the arc's heat, the second is the resistive preheating of the extension, and the application attributes the two-term form to Lesnewich. The balance $MR = WFS$ defines the steady arc, which is found at each reset by bisection on the circuit's residual, bracketed between the current at which the extension would fill the whole CTWD and the one that would burn it back to the tip.

12.3.3 Constant Current and the Droplet

The comparison source regulates the current itself inside a compliance voltage, as shown in Equation (12.3).

$$\frac{\mathrm{d}i}{\mathrm{d}t} = \min\left(\frac{I_{set} - i}{\tau_{cc}},\ \frac{V_{max} - R_c\, i - V_{tip}}{L}\right) \tag{12.3}$$

where the setting I_{set}, the regulator time $\tau_{cc} = 2\,\mathrm{ms}$ and the compliance $V_{max} = 50\,\mathrm{V}$ define the source. A droplet grows on the wire tip over one period of a phase ϕ and shortens the arc while it hangs, as

shown in Equation (12.4).

$$\begin{aligned} \frac{\mathrm{d}\phi}{\mathrm{d}t} &= f_d(i), \qquad f_d = \mathrm{clamp}\Big(f_T\Big(\frac{i}{i_T}\Big)^3,\ 20,\ 500\,\mathrm{Hz}\Big) \\ d &= \Big(\frac{6MRA_w}{\pi f_d}\Big)^{1/3}, \qquad \Delta l_d = \kappa_d F\,\phi\,d \end{aligned} \tag{12.4}$$

where A_w is the wire's cross-section, d the droplet diameter, $\kappa_d = 0.5$ the share of it that shortens the arc, and F a size factor. When ϕ reaches 1 the droplet detaches, ϕ drops back by one and F is drawn as $\mathrm{clamp}(1 + 0.15\,n,\ 0.5,\ 1.6)$ with n standard normal. At the default arc the model sheds 225.6 droplets a second, about nine physics steps per droplet, and the ripple they leave is the sawtooth on the scope.

12.3.4 Travel and the Torch Axes

Travel follows its command through a first-order response with an acceleration limit, and the two correction axes are position loops around velocity loops (Section 1.4.3), as shown in Equation (12.5).

$$\begin{aligned} \frac{\mathrm{d}s}{\mathrm{d}t} &= v, \qquad \frac{\mathrm{d}v}{\mathrm{d}t} = \mathrm{sat}_{a_s}\Big(\frac{v_{cmd} - v}{\tau_s}\Big) \\ \ddot{y} &= \mathrm{sat}_{a_y}\big(\omega_{v,y}\big[\mathrm{sat}_{v_y}\big(\omega_{p,y}(y_{ref} - y)\big) - \dot{y}\big]\big) \\ y_{ref} &= y_C + A\sin\big(\varphi_w + 2\pi f_w(t - t_w)\big) \\ \ddot{z} &= \mathrm{sat}_{a_z}\big(\omega_{v,z}\big[\mathrm{sat}_{v_z}\big(\omega_{p,z}(z_C - z)\big) - \dot{z}\big]\big) \end{aligned} \tag{12.5}$$

where $\mathrm{sat}_m(x)$ limits x to $\pm m$, y_C and z_C are the commanded lateral and height positions, A and f_w the weave amplitude and frequency, and φ_w and t_w the phase and time of the last control update, which keep the weave continuous when its frequency changes. The application's own check drives both axes through a 10 mm step and finds that neither exceeds its rate or acceleration limit while the lateral axis reaches its rate limit.

12.3.5 The Part

The seam, the gap and the plate height are functions of the travel distance, and the seam also moves with the heat put into the part, as shown in Equation (12.6).

$$\begin{aligned} y_{seam} &= y_{off} + a\,s + A_b\sin\frac{2\pi s}{\lambda_b} + k_d\,\frac{E_{arc}(t)}{100\,\mathrm{kJ}}\,\frac{s}{L_s} \\ z_p &= z_r\,\rho(s) + z_{st}\,[s \geq 60\,\mathrm{mm}] \\ y_{arc} &= y + \delta_c\,l_s/11\,\mathrm{mm} \\ CTWD &= z - z_p - \kappa\min\big(|y_{arc} - y_{seam}|,\ (g + W_V)/2\big) \end{aligned} \tag{12.6}$$

where $\lambda_b = 300\,\mathrm{mm}$, $L_s = 1.2\,\mathrm{m}$ is the seam length, $\rho(s)$ rises linearly from 0 to 1 between 100 and 700 mm, δ_c is the wire cast that bends the tip off the torch axis, and the root gap $g(s)$ is the nominal g_0 plus one of three piecewise-linear profiles, constant, opening by 1.1 mm between 150 and 750 mm, or varying, at $-0.2\,\mathrm{mm}$ up to 250 mm, $+1.2\,\mathrm{mm}$ from 550 to 700 mm and $+0.2\,\mathrm{mm}$ beyond 950 mm. The part is clamped at the start of the seam and bows as it heats, so its free end moves k_d millimeters for every 100 kJ of arc energy delivered, and every point of the seam moves with it, welded or not. The groove walls rise by κ per unit of lateral offset as the arc sees them, which is what a weave reads, and both κ and the drift law are illustrative.

12.3.6 The Pool, the Bead and Its Record

The pool integrates the arc's power and loses it as it moves on, and the bead's offset is the arc's offset averaged over the pool's passage, as shown in Equation (12.7).

$$\begin{aligned} \frac{\mathrm{d}E_p}{\mathrm{d}t} &= V_{tip}\,i - E_p\,\frac{\max(v, v_c)}{L_p}, \qquad H = \frac{E_p}{L_p} \\ \frac{\mathrm{d}e_1}{\mathrm{d}t} &= r_b\,(y_{arc} - y_{seam} - e_1), \qquad \frac{\mathrm{d}e_b}{\mathrm{d}t} = r_b\,(e_1 - e_b) \end{aligned} \tag{12.7}$$

where the pool holds the energy E_p over a length $L_p = 8\,\mathrm{mm}$, $v_c = 4\,\mathrm{mm/s}$ stands for conduction into the plate, H is the heat input per unit length, and $r_b = \max(v, 8\,\mathrm{mm/s})/(L_p/4)$, about $L_p/2v$ over the two stages. A moving pool settles at $H = V_{tip}\,i/v$, the heat input the application's check confirms to within 0.5 %, and a stationary one keeps heating toward $V_{tip}\,i/v_c$, which is why the start dwells and the crater fill is short. The bead follows the correlations of Equation (12.8).

$$\begin{aligned} p &= a_p H^{b_p}\,\frac{1+\beta_g g}{1+\beta_A A}, \qquad w = a_w H^{b_w} + k_w A \\ v_{max} &= v_u \Big(\frac{H}{675\,\mathrm{J/mm}}\Big)^{e_u}, \qquad A_n = A_V + t_p\,g \end{aligned} \tag{12.8}$$

where p is the penetration, w the width, v_{max} the travel speed above which the bead undercuts and A_n the metal a millimeter of groove needs to be filled flush. A millimeter lacks fusion when $p < p_{min}$ or when $w/2 - |e_b| < (g + W_V)/2 + m_e$, burns through when $p > t_p$, undercuts when $v > v_{max}(H)$, underfills when its deposit $A_d < A_n$, and is porous when the shielding coverage $\chi = f_{gas}\min\big(1, (18\,\mathrm{mm}/CTWD)^{1/2}\big)$ falls below χ_{min}, with f_{gas} the gas flow as a share of the set flow. At the default 681 J/mm and a 1 mm gap the correlations give $p = 4.23\,\mathrm{mm}$, $w = 8.03\,\mathrm{mm}$ and $v_{max} = 13.1\,\mathrm{mm/s}$, the deposit $\eta A_w WFS/v$ is $14.6\,\mathrm{mm}^2$ per millimeter against a need of $12.0\,\mathrm{mm}^2$, and the heat input window between lack of fusion and burn-through runs from 499 to 1123 J/mm. Every coefficient is a teaching value chosen so that the default procedure sits inside its window. None of it is a qualified procedure, and the real limits come from a procedure qualification record under ISO 15614-1 or AWS D1.1 and from the acceptance levels of ISO 5817, which the application names.

Each millimeter is classified when the arc leaves it, from the pool's heat input, the gap at the millimeter's center, the weave amplitude, the bead offset, the travel speed, the metal deposited into that millimeter and the shielding. Deposit is booked as η times the wire melted, spread over the pool length ahead of the arc during the start dwell and behind it during the crater fill. When the arc goes out, at the end of the seam or on a stop, the last pool length is recorded again with a crater depression $A_{cr} = 4\,\mathrm{mm}^2$ removed from it, so a crater that is not filled underfills. An extension shorter than 0.5 mm ends the weld as a burn-back, an arc longer than 12 mm breaks, a wire driven 1 mm into the pool stubs out, and an arc shorter than 0.3 mm after the droplet is flagged as stubbing.

The current and voltage transmitters are first-order front ends, $\tau_m\,\mathrm{d}i_f/\mathrm{d}t = i - i_f$ and $\tau_m\,\mathrm{d}V_f/\mathrm{d}t = V_{tip} - V_f$ with $\tau_m = 5\,\mathrm{ms}$, and the three ledgers integrate $V_{tip}\,i$, WFS and MR, so that the wire balance and the deposit close to 10^{-9} relative in the application's own check. The constants are collected in Table 12.2.

12.3.7 Initialization and Numerics

Every scenario opens with the arc struck on the start of the seam and the pool cold. The steady arc of the scenario's source and feed at the CTWD setpoint sets the current, the extension, the feed and both transmitters, the droplet is at mid-growth, the torch stands at $z_p(0)$ plus the setpoint, and the travel speed and the pool energy are zero. Before the arc strikes, the laser has already scanned the first 40 mm at 0.5 mm spacing, and with laser tracking the torch starts on the seam it found. Each 0.5 ms

Table 12.2 Model Constants and Where They Live. Adjustable Constants Have a Slider Under Show Model, Hidden Ones Have None, and Fixed Ones Exist Only in the Source

Symbol	Quantity	Value	Access
k_1	arc melting coefficient	0.300 mm/(s A)	adjustable
k_2	resistive melting coefficient	8.48×10^{-5} 1/(s A^2)	adjustable
V_0, E_a	arc falls, column gradient	15.0 V, 1.2 V/mm	adjustable
R_a, R_c	arc, cable and contact tip	22 mΩ, 4 mΩ	adjustable
r_w	hot wire per unit length	0.62 mΩ/mm	adjustable
κ_d	droplet shortening share	0.5	adjustable
i_T, f_T, σ_d	spray transition, scatter	220 A, 150 Hz, 0.15	hidden
τ_{cc}, V_{max}	CC regulator, compliance	2 ms, 50 V	hidden
τ_f, τ_s	feeder, travel lags	30 ms, 50 ms	adjustable
a_s	travel acceleration limit	200 mm/s^2	adjustable
$\omega_{p,y}$, $\omega_{v,y}$	lateral axis gains	36, 70 rad/s	adjustable
v_y, a_y	lateral limits	50 mm/s, 1.0 m/s^2	adjustable
$\omega_{p,z}$, $\omega_{v,z}$	height axis gains	25, 50 rad/s	adjustable
v_z, a_z	height limits	40 mm/s, 1.0 m/s^2	adjustable
L_s, t_p	seam length, plate	1.2 m, 6.0 mm	adjustable
A_V, W_V, κ	groove area, width, wall rise	6 mm^2, 4 mm, 0.6	adjustable
d_{la}	laser as mounted	40 mm	adjustable
L_p, v_c	pool length, conduction	8 mm, 4 mm/s	adj., fixed
a_p, b_p	penetration	0.04184, 0.70	adjustable
β_g, β_A	gap and weave on p	0.05, 0.05 mm^{-1}	adjustable
a_w, b_w, k_w	width	0.3079, 0.5, 1.0	adjustable
p_{min}, m_e	fusion, edge margin	3.4 mm, 0.3 mm	adjustable
v_u, e_u	undercut speed	13 mm/s at 675 J/mm, 0.8	adjustable
χ_{min}, η, A_{cr}	shielding, deposition, crater	0.6, 0.97, 4 mm^2	adjustable
σ_L, p_{drop}	laser noise, dropouts	0.05 mm, 1 %	adjustable
σ_I, σ_V	current, voltage noise	1.5 A, 0.15 V	adjustable
τ_m	transmitter front ends	5 ms	hidden
l_{min}, λ_b	arc floor, bend wavelength	0.1 mm, 300 mm	fixed

step of the model is one fourth-order Runge-Kutta step, because the circuit's 6.3 ms and the droplet period of about 4.4 ms are the fastest dynamics, while the controller and the laser run every 20 ms and the historian logs a row every 20 ms. Halving the step moves the peak and settled current and the arc length at 100 ms and at steady state by at most 0.66 %, against the application's 1.5 % limit. The engine, the speed selector and the seeding are those of Section 1.6.1. Here the speed selector ranges from a quarter of real time to twice it, a 1.2 m seam at 10 mm/s takes 121.6 s, at a quarter of real time the scope resolves single droplets, and the droplet sizes, the sensor noise and the laser dropouts come from streams seeded at reset from seed 20261102.

12.3.8 Assumptions

The arc is a lumped melting rate with a linear arc characteristic, whose coefficients the application describes as typical of 1.2 mm steel wire in an argon-rich gas, not fitted to one wire. The extension has one hot resistance per millimeter, where dynamic models of the extension carry a temperature-dependent resistivity [12]. Transfer is spray only, a droplet sawtooth on the arc length rather than a dynamic model of drop detachment [14], so short-circuit and globular transfer are absent and a wire driven into the pool is an event rather than a transfer mode. This breaks down below the 220 A transition and in any procedure that relies on short circuits.

The sources are ideal characteristics, a line with a slope and an inductance and a 2 ms current regulator inside a 50 V compliance, so the waveform control of an inverter source is outside the model, and the synergic line is represented only as a source voltage that follows the scheduled feed. The robot is three Cartesian axes with exact encoders, so arm kinematics, torch angles, path interpolation and the robot's own sensor interface delay are outside the model.

The joint is one single-V butt joint welded in one pass, the groove walls act on the arc through a linear rise, and the distortion is a rotation about the start of the seam in proportion to the arc energy,

whereas the distortion of a real thin-plate butt joint is predicted together with its residual stress [17]. The pool is one lumped energy of fixed length, the start and the crater are approximations over that length, and heat does not carry over from one seam to the next. The laser measures points of the groove with Gaussian noise and random dropouts and does none of the seam feature extraction that the tracking literature reviews [8], so reflections, smoke and tack welds do not exist for it. The bead correlations and defect rules are illustrative throughout.

> **OPEN CHALLENGE** **Narrow Gaps Hide From Both Sensors**
>
> A narrow joint defeats both sensors of this chapter. Arc sensors have been studied since the 1980s and sold for T and V grooves, but in narrow gap welding their arc stability and sensing accuracy are not satisfactory [19]. A laser stripe finds little to bend at a gap under 0.2 mm, and methods that add lighting or images of the joint ask for strict illumination of the surface [20]. Progress would be one sensor that finds the three-dimensional position and the surface of a narrow joint on any finish, near the arc.

12.4 The Arc's Own Loop

The circuit's time constant, 6.3 ms, is short against the recovery of the arc, so the self-regulation can be read from the model with the inductance and the droplet set aside. The current is then algebraic, and linearizing Equations (12.1) and (12.2) about a steady arc gives a first-order loop in the extension, as shown in Equation (12.9).

$$\begin{aligned} \frac{\mathrm{d}\,\delta l_s}{\mathrm{d}t} &= -\lambda\,\delta l_s + \mu\,\delta CTWD \\ \lambda &= \left(k_1 + 2k_2\,l_s\,i\right)\frac{E_a - r_w\,i}{R_\Sigma} + k_2\,i^2 \\ \mu &= \left(k_1 + 2k_2\,l_s\,i\right)\frac{E_a}{R_\Sigma} \end{aligned} \tag{12.9}$$

where the first term of λ is the arc's share of the loop, a longer extension shortening the arc and raising the current by $(E_a - r_w i)/R_\Sigma$ per unit length, and the second is the extension's own resistive preheating. At the default arc the two shares are 16.6 and 5.38 s^{-1}, so $\lambda = 22.0\,\mathrm{s}^{-1}$ and the time constant of self-regulation is $\tau_{sr} = 1/\lambda = 45.5$ ms. A first-order loop reaches 90 % in $2.303\,\tau_{sr} = 104.7$ ms, and the full nonlinear model restores 90 % of the 3 mm step of case 1 in 97.0 ms, as shown in Figure 12.2. The droplet sizes are random, and eight other seeds give 96.5 to 100 ms. The source slope enters through R_Σ. With no slope and 28.0 V open circuit, which keeps the same weld, the linearization gives 77.7 ms against a measured 66.5 ms, and at 3 V per 100 A and 35.6 V it gives 127.8 ms against 120.0 ms. One likely reason the 3 mm step recovers faster than the small-signal estimate in all three is that the melting rate grows with the square of the current, which overshoots to 336.1, 316.5 and 304.0 A.

> **TRY IT IN THE APP** **1 · The Arc Regulates Itself**
>
> Load the case and press Run on the Arc view. About 7 s in, the torch meets the 3 mm plate step. Watch the current on the scope jump toward 316 A and decay while the side view shows the arc growing back, with no loop acting in MANUAL. Press Reset, set Power source to Constant current on the Power source card and run again: the arc stays short.

The same linearization gives the current's response to the distance, as shown in Equation (12.10).

$$G(j\omega) = \frac{\delta i}{\delta CTWD} = -\frac{E_a}{R_\Sigma}\,\frac{j\omega + k_2\,i^2}{j\omega + \lambda} \tag{12.10}$$

A change too fast for the extension to follow meets the full $E_a/R_\Sigma = 25.2$ A per millimeter, while at steady state the extension burns back and leaves 6.16 A per millimeter, close to the 6.12 A per

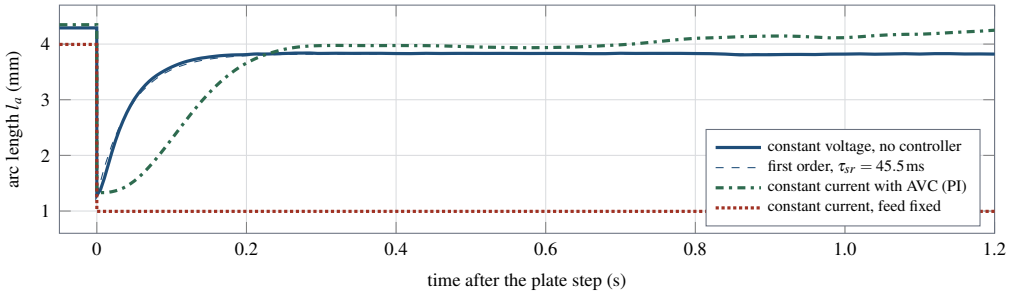


Figure 12.2 Arc length after the 3 mm plate step of case 1 at 6.95 s, for three sources on the same procedure. The constant-voltage arc (thick solid) regulates itself with no controller and follows the first-order response of Equation (12.9) (thin dashed) closely. The constant-current arc with a fixed feed (thick dotted) stays 3 mm short, and the arc-voltage-controlled feed (thick dash-dotted) restores it through a PI loop.

millimeter that the controller computes by bisection with the droplet at mid-growth. For the 3 mm step of case 1 the steady solution gives 251.9 A at 15 mm and 272.3 A at 12 mm, and the engine settles 20.5 A higher. Between the two limits lies the weave. At 3 Hz the magnitude of Equation (12.10) is 17.0 A per millimeter, 2.77 times its steady value, and a weaving tracker that divides by the steady sensitivity has to carry a calibration of that size. The application carries 2.5, measured at its default 1.5 mm and 3 Hz weave. At 2 and 4 Hz Equation (12.10) changes by factors of 0.80 and 1.14 relative to 3 Hz, and the calibrated tracker reads a known 0.3 mm offset as 0.16 to 0.23 mm at 2 Hz and 0.38 to 0.40 mm at 4 Hz, larger departures than the linear model because the lateral axis and the averaging near each extreme likely add their own dependence on frequency.

A constant-current source removes the loop. The melting balance at a fixed 250 A fixes the extension at 11.01 mm whatever the distance, so the arc takes the whole step, from 3.99 to 0.99 mm, and the torch voltage falls from 26.67 to 23.07 V. The arc-voltage-controlled feed (AVC) closes the loop around the voltage instead, on a plant that a manual feed step measures at −3.30 V per m/min with 63 % of the response in 227 ms. With the 1 s integral time the loop recovers 85 % of the length it holds 1.5 to 2.3 s after the step by 0.3 s and creeps the rest, reaching 90 % of it in 834.5 ms with the feed at 6.90 m/min. The creep is slow enough for the noise to move that time, which eight other seeds put between 858 and 996 ms. A counterfactual run without the integral term, which the 5 s upper end of the integral-time slider does not reach, recovers 70 % of the same length by 0.3 s and then holds the arc near 3.2 mm, 1.2 mm shorter. A larger inductance slows the current rather than the arc. At 1 mH the current peaks 39.0 ms after the step at 305.1 A, against 17.5 ms and 316.5 A at 0.3 mH, and the arc is 90 % restored in 93.5 ms.

🕮 **Pause.** Try Exercise 12.1 before reading on.

12.5 Implemented Controller

The cell controller executes every $\Delta t_c = 20$ ms, forty physics steps, in the order of Section 1.6.1, with the droplets, events and bead record booked after each integration. No loop reads the part or the arc directly.

12.5.1 Instruments

The encoders report s, y and z exactly, the feeder tachometer reports WFS, and the current and torch voltage are sampled from the transmitter states with Gaussian noise of 1.5 A and 0.15 V. The laser returns the groove's center, root gap and height at $s + d_{la}$ every 20 ms, each with 0.05 mm of noise, and loses 1 % of its readings plus the spatter share, or all of them while its window is covered. The gas flow switch carries 1 % noise.

Table 12.3 Loops, Directions and Shipped Settings. All Execute Every 20 ms

Loop and law	Measurement	Actuator	Setting
HC, PI, $\gamma = +1$	$\widehat{CTWD}$ or laser	Δz	$K_c = 0.5$, $\tau_I = 0.25$ s
AVC, PI, $\gamma = -1$	V_m, 40 ms filter	*WFS*	$K_c = 0.5$, $\tau_I = 1$ s
TC, laser, Eq. (12.12)	$\hat{y}_{seam}(s + v\tau_{lead})$	Δy	$K_t = 0.5$
TC, weave, Eq. (12.14)	$\hat{\Delta}$ per cycle	Δy	$K_t = 0.5$
trim, integral	$\hat{\Delta}$ per cycle	y_{trim}	$K_{trim} = 0.2$
fill, Eq. (12.15)	$\hat{g}$ at the torch	*WFS* or v	$A_r = 2\,\text{mm}^2$

Δz, Δy within ± 10 mm, *WFS* 1.5 to 18 m/min. Gains in mm per mm (HC), m/min per V (AVC) and per update (K_t, K_{trim}).

12.5.2 The PI Algorithm

The height loop (HC) and the AVC loop call the framework's one velocity-form routine, Equations (1.19) to (1.22) of Section 1.6.2, executed every Δt_c. This chapter writes the controller action as $\gamma = \pm 1$, because a is the seam angle here. The height loop has $\gamma = +1$ and is reverse acting, since raising the torch lengthens the CTWD. The AVC loop has $\gamma = -1$ and is direct acting, since more feed shortens the arc and lowers the torch voltage. In both loops the output bias is zero, the tracking time T_t equals τ_I, and $\tau_D = 0$. The running sum is never clamped, and back-calculation corrects only the integral. In MANUAL, and whenever a loop is not live, it tracks so that its output follows the operator's station, its own last output or, for the AVC on a constant-voltage source, the scheduled feed, and a return to automatic is bumpless. The loops and their shipped settings are collected in Table 12.3.

12.5.3 Height Through the Arc

The height loop holds the CTWD at its 15 mm setpoint by adding Δz to the taught height, reading the CTWD from the laser's buffered groove height at the torch or through the arc. The through-the-arc estimate inverts the steady melting balance of Equation (12.2) and the arc voltage of Equation (12.1) from the measured current, voltage and feed, as shown in Equation (12.11).

$$\begin{aligned} \hat{I}_s &= \frac{WFS - k_1 \bar{I}}{k_2 \bar{I}^2} \\ \widehat{CTWD} &= \hat{l}_s + \frac{\bar{V} - V_0 - R_a \bar{I} - r_w \hat{l}_s \bar{I}}{E_a} + \frac{\kappa_d d}{2} \end{aligned} \tag{12.11}$$

where $\bar{I}$ and $\bar{V}$ are the samples averaged by a 0.15 s first-order filter that removes the droplet ripple, and d is the droplet diameter at $\bar{I}$ and the feed. The coefficients are the controller's own copy of the model, taken at reset, so a parameter changed during a run biases the estimate as a wire change would. On the flat start of case 2, between 3 and 10 s with the height loop closed through it, the estimate reads the CTWD 0.042 mm short with a scatter of 0.065 mm (1σ), while eight other seeds put that bias between 0.005 and 0.044 mm. It is right only once the arc has settled. After the 3 mm step of case 1 it reads 12.08 mm at the scan 90 ms after the step and dips to 11.87 mm, and its scatter last carries it more than 0.15 mm from 12 at 1.45 s, a time that eight other seeds spread from 0.07 to 3.0 s. The loop holds its output while the torch fills the crater, while the laser it reads is blind, and when the arc is on a constant-current source, whose current carries no height.

12.5.4 The Preview Buffer and Laser Tracking

The laser line falls $d_{la} = 40$ mm ahead of the arc, but the buffer knows nothing about the bracket. The controller files each reading under a key made of the torch's encoder position when the reading was taken and the look-ahead it believes the sensor sits at, and it asks for the reading at the torch's own

position, as shown in Equation (12.12).

$$\begin{aligned} k_j &= s_j + d_{cfg}, \qquad \hat{y}_{seam} = \mathscr{B}\big(s + v\,\tau_{lead}\big) \\ \Delta y_k &= \Delta y_{k-1} + K_t\big(\hat{y}_{seam} + y_{SP} + y_{trim} - \Delta y_{k-1}\big) \end{aligned} \tag{12.12}$$

where s_j is the torch position at reading j, d_{cfg} the configured look-ahead, $\mathscr{B}(q)$ the buffer's value at key q, $\tau_{lead} = 30\,\text{ms}$ a lag compensation for the lateral axis, y_{SP} an offset setpoint, and y_{trim} the through-the-arc trim when it is on. The buffer holds 6000 readings in a ring. It interpolates between valid readings at most 1.5 mm apart, holds the last valid reading for up to 10 mm beyond it, and then reports the laser blind. Section 1.4.6 corrects a report for its age in time. Here a reading belongs to a place along the seam instead, and its age in time does not matter. The tracking law is a first-order approach with an equivalent time constant of 28.9 ms at $K_t = 0.5$, and the gap and the plate height are read at the torch itself, without the lead.

A wrong d_{cfg} files every reading at the wrong place, and nothing in the readings can reveal it. The torch at s receives the reading taken when it stood at $s - d_{cfg}$, which describes the seam at $s + \Delta d$ with $\Delta d = d_{la} - d_{cfg}$, so on a bend of amplitude A_b the lateral error is $y_{seam}(s + \Delta d) - y_{seam}(s)$, whose largest value is $2A_b\lvert\sin(\pi\Delta d/\lambda_b)\rvert$, as shown in Equation (12.13).

$$e_{max} = 2A_b\left|\sin\frac{\pi\,(d_{la} - d_{cfg})}{\lambda_b}\right| \tag{12.13}$$

The error peaks where the seam crosses the taught path at its steepest and vanishes at the crests, where the seam runs parallel to the path, and a bead that must reach both groove edges loses fusion wherever $|e_b|$ exceeds $w/2 - (g + W_V)/2 - m_e$, 1.22 mm at the default procedure.

> **TRY IT IN THE APP** **4 · The Look-Ahead Set Wrong**
>
> Run the case on the Seam view. The amber readings end 20 mm short of the laser line, and the bead leaves the groove where the seam crosses the taught path. Press Reset, set Look-ahead distance (configured) to 40 mm on the TC card and run again. The worst offset falls from 1.451 to 0.067 mm.

12.5.5 Tracking Through the Weave

With a weave, the arc approaches one groove wall at each extreme. The controller averages the measured current while the encoder puts the torch more than $0.7A$ from the weave center on either side and, once per weave cycle, converts the difference into the torch's offset from the groove center, as shown in Equation (12.14).

$$\hat{\Delta} = \frac{\bar{\imath}_R - \bar{\imath}_L}{2\,\kappa G_0\,c}, \qquad \Delta y \leftarrow \Delta y - K_t\big(\hat{\Delta} - y_{SP}\big) \tag{12.14}$$

where $\bar{\imath}_R$ and $\bar{\imath}_L$ are the mean currents near the right and left extremes, G_0 is the steady sensitivity of the current to the CTWD that the controller recomputes from its model every cycle, and $c = 2.5$ is the calibration of Section 12.4. A torch to the right of the groove center sees the right wall sooner, a shorter distance and a higher current, and is moved left. In the laser with arc trim mode the laser law of Equation (12.12) runs every 20 ms and the trim integrates $y_{trim} \leftarrow y_{trim} - K_{trim}\hat{\Delta}$ once per cycle. When the laser is blind and the torch is weaving, the fallback, if it is on, switches the lateral correction to Equation (12.14). Without a weave there is nothing to fall back on, and the correction holds.

12.5.6 Adaptive Fill and the Synergic Line

The fill law schedules the feed or the speed on the gap the laser measured at the torch, as shown in Equation (12.15).

$$\begin{aligned} A_t &= A_V + t_p\,\hat{g} + A_r \\ \text{by feed:}\quad WFS &= \max\left(WFS_{SP},\ A_t\,v/(\eta A_w)\right) \\ \text{by speed:}\quad v &= \min\left(v_{SP},\ \eta A_w WFS_{SP}/A_t\right) \\ V_{oc,cmd} &= V_{oc} + k_{syn}\left(WFS - WFS_{SP}\right) \end{aligned} \tag{12.15}$$

where A_r is the reinforcement target above the groove, $k_{syn} = 1.2\,\mathrm{V}$ per m/min is the synergic slope, and the feed is clamped to 1.5 to 18 m/min. By feed, wire is added only when the gap needs more than the procedure deposits, so a narrow gap keeps the procedure's heat. By speed, the torch slows down at the procedure's feed. Both add heat to add metal, which is the limit case 5 finds. The fill law is feedforward from a measured disturbance, like the coagulant dose computed from the raw water turbidity in Volume 3, Chapter 6, and like any feedforward it is bounded by what the plant can take.

12.5.7 The Window Guard and the Supervisor

The window guard runs every tenth control step, or whenever the scheduled speed changes, and asks the bead correlations whether the asked speed is sound at the measured gap with a margin of 0.05 on every rule, using the steady arc at the CTWD setpoint and the fill law's feed. If it is not, the guard searches down in steps of 0.5 mm/s to 3 mm/s, bisects ten times for the fastest sound speed and holds the travel there. It also tests 33 feeds from 1.5 to 18 m/min, each at its synergic voltage, and reports the asked speed as infeasible when none of them welds it.

The supervisor starts the arc with the torch still for a 0.9 s dwell, welds, brakes into the end of the seam on $v_{cmd} = \min\left(v_{sched}, \sqrt{2 \cdot 0.9\,a_s\,(L_s - s - 0.2\,\mathrm{mm})}\right)$, with v_{sched} the speed after the fill law and the guard, fills the crater for 0.5 s at half the procedure's feed, no more than 5 m/min, and switches the arc off. It marks the laser blind when the buffer has no usable reading, and it stops the weld when the flow switch reads below 70 % for 0.3 s with the gas stop on.

12.5.8 Plant, Measured and Internal Models

The equations of Section 12.3 are the simulation model. The application carries no identified control model, and manual steps on the flat plate of case 2 measure what the loops see, each read as the stepped run less an otherwise identical unstepped one. A 1 mm step of the height station moves the true CTWD by 1.000 mm, 63 % of the way 51 ms after the scan that applies it, and the through-the-arc estimate by 0.998 mm in 101 ms, while the filtered current falls by 5.9 A. The AVC plant is the −3.30 V per m/min of Section 12.4. The controller's internal models are the inversion of Equation (12.11) and its sensitivity G_0, the calibration c and the wall rise κ of Equation (12.14), the configured look-ahead d_{cfg}, the groove need and deposit of Equation (12.15), and the bead correlations and steady arc inside the guard. None of them models the part's drift.

12.6 Measured Cases

Table 12.4 names the eight cases and the graded seam. Each case starts from the procedure of Section 12.1, with constant voltage, no height control, no tracking, weave, fill or guard, the start dwell, the crater fill and the gas stop, and differs from it only in what its row lists, except that cases 4 to 8 track the seam with the laser and cases 6 and 7 also weave 1.5 mm. Every number quoted below was measured by driving the engine from a script at the default seed, with each change made after the case is selected and before the run, as a learner makes it, which gives the same run as the change carried through a Reset (Section 1.6.4). Times are in simulated seconds, and the bead record of each run is summarized in Table 12.5. Positions along the seam are the lower edge of the first millimeter concerned. Worst offsets are partly set by the laser and sensor noise, and where a comparison is within its spread over eight other seeds the text says so. Figure 12.3 draws the bead record as bars.

Table 12.4 Scenarios, With the Disturbance Each Imposes

#	Scenario and disturbance	Teaching point
1	3 mm plate step at 60 mm, MANUAL	a loop with no controller
2	plate rises 4 mm, 100 to 700 mm	the current as a sensor
3	seam 2.5 mm off the taught path	preview places the torch
4	look-ahead set to 20 mm, bend 3.5 mm	a reading used early
5	gap opens 1.0 to 2.1 mm	adaptive fill, its limit
6	drift 1.0 mm per 100 kJ, weave	a preview 4 s old
7	laser blind 12 to 30 s, bend 2.5 mm	hold, fall back, stop
8	travel 10 to 14 mm/s at 20 s	the undercut boundary
9	gap 0.8–2.2 mm, offset 1 mm, 12.5 mm/s	graded seam

Table 12.5 Bead Record of Each Case and Variant Over the Whole 1200 mm Seam. LoF Is Lack of Fusion, BT Burn-Through, UC Undercut, UF Underfill and P Porosity

Case and configuration	Defect (mm)	Kind	Worst $\lvert e_b \rvert$ (mm)
2 height off, through the arc, laser	0	—	0.000
3 tracking off	1200	LoF	2.500
3 laser	0	—	0.041
3 through the arc, 1.5 mm weave	10	LoF	2.541
5 fill off	810	UF	0.041
5 fill by feed, by speed	0	—	0.051
5 by feed, gap opening to 2.5 mm	536	BT	0.041
6 laser	0	—	0.380
6 tracking off	610	LoF	8.429
6 laser with trim, through the arc	0	—	0.154, 0.233
7 hold the last reading	63	LoF	2.605
7 fall back to the arc	0	—	0.527
7 fall back, no weave	103	LoF	2.515
7 gas loss at 45 s, stop off	823	LoF, P	2.605
8 14 mm/s as shipped	1008	LoF, UC, UF	0.028
8 14.5 m/min at 39.6 V, or the guard	0	—	0.028, 0.025

12.6.1 The Arc Regulates Itself

Case 1 welds in MANUAL at 8 m/min and 31.8 V. Over the second before 6 s the arc carries 252.1 A at 27.05 V with a 4.29 mm arc, and over 0.3 s the scope shows the current between 250.7 and 254.7 A and the torch voltage between 26.56 and 27.41 V. The torch meets the step at 6.95 s. The arc is suddenly 1.28 mm long, the current peaks at 316.5 A after 17.5 ms, and the arc is back to 3.01 mm after 50 ms, 3.59 mm after 100 ms and 3.82 mm once settled, 90 % restored at 97.0 ms, with the current settled at 272.6 A and the torch voltage at 26.66 V. The run 100 ms after the step is shown in Figure 12.4. The laser met the same step 4.0 s earlier, 40 mm at 10 mm/s, and the buffered height at the torch changes on the torch's arrival, as the application's own check confirms.

12.6.2 The Current as a Height Sensor

Case 2 raises the plate 4 mm between 100 and 700 mm. With the height loop off the CTWD falls from 15.00 to 11.00 mm, and the filtered current rises from 251.2 A at 5 s to 274.9 A at 60 s, where the CTWD is 11.73 mm, and to 280.5 A on the raised plate, about 7 A per millimeter. The pool's heat input rises from 681 to 743 J/mm and the penetration from 4.23 to 4.49 mm. The bead stays sound over all 1200 mm, but it is welded 4 mm closer than its procedure. Taken through the arc, the height loop reads that current as a distance and raises the torch with the plate, holding the CTWD between

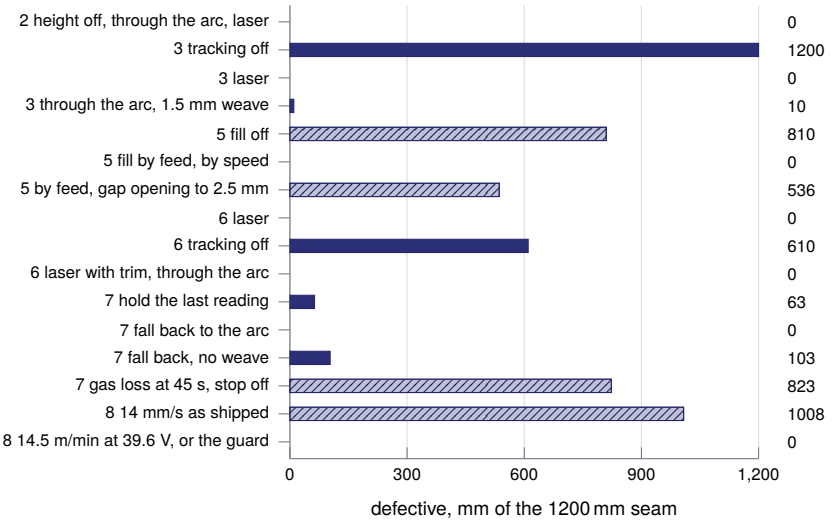


Figure 12.3 The bead record of Table 12.5 drawn as bars, labeled by case and configuration: the millimeters of the 1200 mm seam recorded defective. Solid bars lack fusion only, hatched bars carry underfill, burn-through, porosity or undercut, and a row with no bar welds the whole seam sound. Notice that every case has a configuration with no bar, and that the hatched bar of case 5 is the fill law itself, pushed to a wider gap.

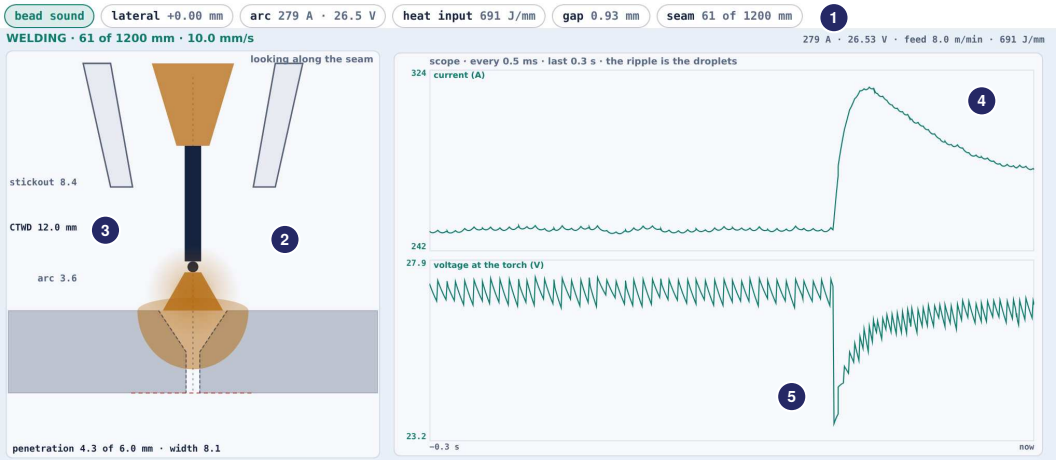


Figure 12.4 Scenario 1, The arc regulates itself, in MANUAL on the Arc view, cropped to the plant view, at $t = 7.05$ s, 0.10 s after the torch met the 3 mm plate step, with no control changed. (1) The badges read a sound bead, a lateral offset of +0.00 mm, 279 A at 26.5 V, 691 J/mm, a laser gap of 0.93 mm and 61 mm of 1200 mm welded at 10.0 mm/s. (2) The side view looking along the seam shows a 3.6 mm arc over a pool 8.1 mm wide that penetrates 4.3 mm of the 6.0 mm plate, (3) with a CTWD of 12.0 mm and a stickout of 8.4 mm. (4) The 0.5 ms scope over the last 0.3 s shows the current leaving its droplet ripple near 252 A toward 316 A and decaying, (5) while the torch voltage drops by more than 3 V and recovers with the droplet sawtooth.

14.87 and 15.13 mm and the current between 250.6 and 253.3 A. The laser's groove height holds it between 14.93 and 15.04 mm. Closed on the 3 mm step of case 1 instead, the through-the-arc loop

brings the CTWD back within 0.5 mm of its setpoint for good after 1.01 s, ten times the 97.0 ms in which the arc restored its own length.

The inference is only as good as the controller's copy of the model. Raising k_2 by 10 %, to 9.30×10^{-5} 1/(s A^2), at 5 s of case 2 with the height read through the arc lowers the true CTWD from 15.05 to 14.22 mm (means over 3 to 5 and 7 to 9 s). The plant now melts the wire faster than the controller's copy predicts, so the inversion of Equation (12.11) reads the CTWD long and the loop lowers the torch. The bias stays until a Reset, which keeps the new coefficient and recopies it into the controller's model, and the CTWD then holds 15.04 mm.

12.6.3 Preview and the Misfiled Reading

Case 3 sets the part 2.5 mm off the taught path. Without tracking, the 8.1 mm bead ends 4.1 mm to the seam's side of the torch while the groove's far edge lies at 5.0 mm, so every millimeter lacks fusion, and the arc on the wall top draws 260.3 to 263.0 A. With the laser, the seam found by the scan before the arc struck places the torch on it and the buffered readings keep it there, with a worst bead offset of 0.041 mm (0.027 to 0.121 mm over eight other seeds). Tracking through the arc with a 1.5 mm weave has to find the seam from its own current, and 10 mm at the start lack fusion while it pulls in from 2.5 mm. With the laser but no start dwell, the first 10 mm lack fusion, nine of them also undercut, the first millimeter frozen from a pool at 117 J/mm.

Case 4 bends the seam 3.5 mm to either side every 300 mm and configures the look-ahead at 20 mm. The torch follows the seam 20 mm further on, the worst offset is 1.451 mm against the 1.455 mm of Equation (12.13), and 372 mm lack fusion in runs of about 48 mm every 150 mm, centered where the seam crosses the path at its steepest. The Seam view shows the fault before any bead does, because the readings, drawn where they were filed, end 20 mm short of the laser line. Swept over configured look-aheads of 30, 50 and 60 mm, the worst offset is 0.728, 0.823 and 1.488 mm against 0.732, 0.732 and 1.455 mm from Equation (12.13), and only 60 mm loses fusion as well, over 397 mm. Filing 20 mm too far ahead errs slightly more than filing 20 mm too near on every seed tried, likely because a reading used late adds to the residual lag of the axis and the pool while one used early offsets part of it, but the 30 and 50 mm pair lies within the noise, which spreads the 30 mm result from 0.721 to 0.821 mm over eight other seeds. With the look-ahead at 40 mm the worst offset is 0.067 mm, and removing the 30 ms lag compensation moves it only to 0.073 mm, inside the 0.042 to 0.122 mm that other seeds give with it. A slow through-the-arc trim does not rescue a wrong look-ahead on this seam, and with a 1.5 mm weave the worst offset becomes 1.501 mm, although the wider bead then covers both edges.

🕮 **Pause.** Try Exercise 12.2 before reading on.

12.6.4 Adaptive Fill and Its Limit

Case 5 opens the gap from 1.0 to 2.1 mm between 150 and 750 mm. At 8 m/min and 10 mm/s the procedure deposits 14.6 mm^2 per millimeter, enough for a gap of 1.44 mm, and without the fill law the bead underfills from 389 mm to the end, 810 mm in all. Filling by feed raises the feed with the measured gap, to 11.18 m/min at 900 mm with the source at 35.65 V, and every millimeter is sound, with the pool's heat input peaking at 1029 J/mm and the wire used rising from 16.18 to 20.11 m. Filling by speed also welds the whole seam sound, slowing to 7.00 mm/s at 900 mm, but the seam takes 150.9 s instead of 121.6 s. Neither law has room to spare. With the nominal gap at 1.4 mm, so that it opens to 2.5 mm, filling by feed burns through from 663 mm, 536 mm in all, and filling by speed from 675 mm. The extra metal brings more heat than the open root can take.

> ✦ DID YOU KNOW? **More Metal, Then a Hole**
>
> From the simulator: in case 5, filling by feed welds the whole seam sound as the gap opens to 2.1 mm. Opened to 2.5 mm, the same law burns through 536 mm of the seam, while no fill at all leaves 810 mm underfilled (Table 12.5). Extra wire brings extra heat.

12.6.5 A Part That Moves, and a Blind Laser

Case 6 lets the part bow by 1.0 mm per 100 kJ while the torch weaves 1.5 mm, and the 836 kJ of the seam move the far end 8.36 mm. Without tracking the bead ends 8.43 mm off the seam and 610 mm lack fusion from 577 mm. With the laser, each reading is 4 s old when the torch arrives, so the bead drifts up to 0.380 mm off, sound but most of a 0.5 mm tolerance. The through-the-arc trim reads the groove at the torch and brings the worst offset to 0.154 mm, and the weave alone gives 0.233 mm. The preview is early but old, the arc current fresh but late, and the two together beat either alone on every seed tried. The wafer stage of Volume 14, Chapter 4 pairs a sensor ahead of its slit with a trailing trim for the same reason.

🕮 **Pause.** Try Exercise 12.3 before reading on.

Case 7 covers the laser's window from 12 to 30 s on a seam bending 2.5 mm. The buffer's 40 mm of readings and the 10 mm hold keep the torch sighted until the scan at 16.96 s, and the first new reading reaches it at 33.98 s. Holding the last reading keeps the torch straight while the seam curves away, and 63 mm lack fusion between 195 and 260 mm (57 to 64 mm over eight other seeds) with the bead 2.60 mm off. Falling back to the weave keeps every millimeter sound at a worst offset of 0.527 mm, and without a weave the fallback has nothing to read and 103 mm lack fusion. A shielding loss fired at 45 s trips the flow switch at the scan 0.28 s later and the supervisor stops the weld at 443 mm, leaving 8 mm of porous, unfilled crater, while with the stop off 760 mm are porous.

12.6.6 The Speed Window and an Honest No

Case 8 raises the travel speed from 10 to 14 mm/s at 20 s, with the feed and the voltage unchanged. The heat input falls to 486 J/mm, below the 499 J/mm the fusion rule needs at this gap, the undercut speed falls to 10.0 mm/s, and the deposit falls to 10.4 mm^2 against a need of 12, so 1008 mm are defective from 191 mm, all of them underfilled, 1001 mm undercut and 980 mm short of fusion. Raising the feed to 14.5 m/min at 39.6 V at the speed change welds every millimeter sound at 14 mm/s, in 92.7 s and with 20.17 m of wire. The window guard instead holds the speed at 11.28 mm/s, where undercut is the binding rule at its 5 % margin, and the seam takes 110.1 s. With adaptive fill by feed as well, the guard holds the speed between 11.6 and 12.4 mm/s, a cap that follows the noise on the gap it measures, and the seam takes 105.0 s. Asked for 18 mm/s, the guard finds no feed between 1.5 and 18 m/min on the synergic line that welds it, reports the speed infeasible and holds 11.28 mm/s. At a 1.0 mm gap the fastest sound speed inside the feeder's range is 17.1 mm/s, at 18.0 m/min and 465 A.

12.6.7 The Graded Seam

The challenge welds 1.2 m at 12.5 mm/s over a gap varying between 0.8 and 2.2 mm, on a part set 1 mm off its path whose free end drifts 0.22 mm per 100 kJ, and asks for every millimeter in specification, the bead within ± 0.5 mm of the seam and an average of at least 12 mm/s over the arc-on time, dwell and crater included, as compared in Table 12.6.

As shipped, with no tracking, no fill and the default procedure, 1198 mm of the 1200 mm are defective and the bead runs up to 2.48 mm off the seam. The suggested configuration welds every millimeter sound with a worst offset of 0.133 mm, 0.37 mm inside the band (0.072 to 0.121 mm over eight other seeds), while the far end drifts 2.04 mm, the feed rises to 14.35 m/min at the widest gap and the pool's heat input peaks at 962 J/mm, for 925 kJ of arc energy. Each element pays for itself. Without the fill law 503 mm underfill where the gap is wide, and with the default 8 m/min at 31.8 V the narrow stretch undercuts over 331 mm, because at 12.5 mm/s that procedure's 544 J/mm puts the undercut speed at 10.9 mm/s. Without tracking, the offset and the drift take the bead off the groove

Table 12.6 The Graded Seam, Shipped, Suggested and With One Element of the Suggestion Removed. Every Run Averages 12.30 mm/s

Configuration	Defect (mm)	Kind	Worst (mm)	Wire (m)
shipped	1198	LoF, UC, UF	2.480	12.98
suggested[a]	0	—	0.133	18.08
suggested, fill off	503	UF	0.133	16.22
suggested, 8 m/min at 31.8 V	331	UC	0.131	17.18
suggested, tracking off	867	LoF	3.071	18.08

[a] laser tracking, fill by feed, 10 m/min at 34.2 V, 12.5 mm/s, $A_r = 1\,\text{mm}^2$

edge from 333 mm. Every run finishes at 12.30 mm/s, so quality and precision alone decide the target, which the application judges on the step that fills the crater, at 97.58 s.

12.7 Technology in Practice

The cell of Section 12.3 reads a laser, the current, the voltage, the feed and the encoders, and it moves two axes, the feed and the source voltage. Figure 12.5 draws its loops with real devices in the place of the schematic's symbols.

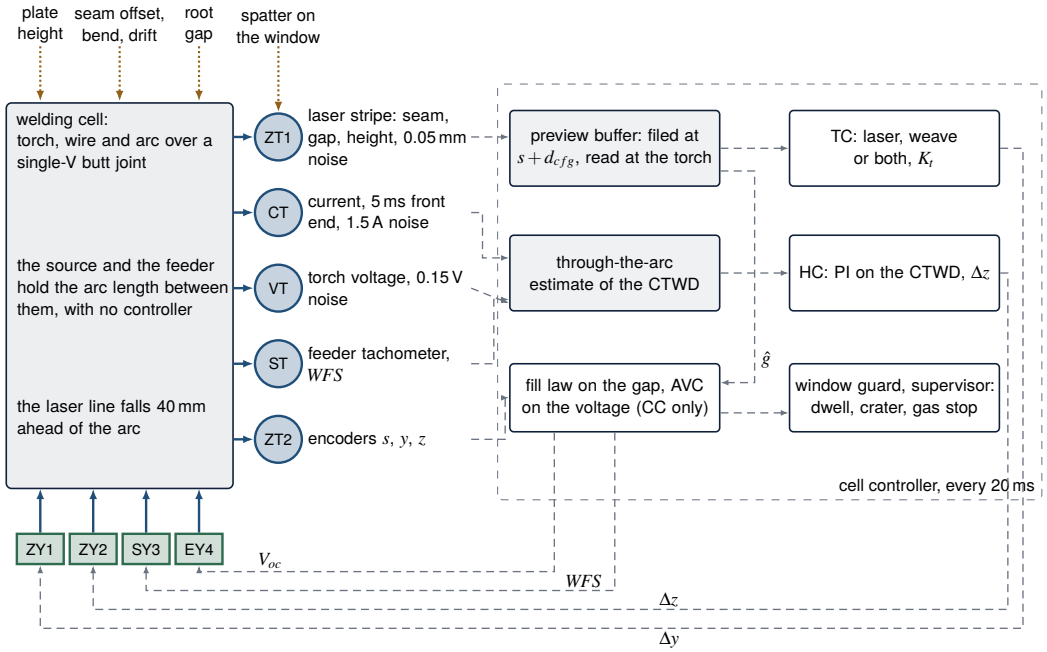
What Measures It

Through-the-arc sensing needs only current and voltage sensors, with the wire feed speed sometimes added, and its sensors sit well away from the weld. In one laboratory cell a Hall-effect transducer in the welding circuit measured up to 600 A within 1 %. The arc voltage cannot be read alone: across the source it includes the drops along the cables, at the contact tube and along the extension, and moving the leads to the torch and the work removes only the cable drop [21]. The transmitters of Section 12.5, with 5 ms front ends and noise of 1.5 A and 0.15 V, stand for such sensors. A laser triangulation unit on the torch gives the distance to the work and the joint as well, at a cost in price, size and intrusiveness [21]. An arc sensor, by contrast, coincides with the arc and resists the arc's light [19]. The laser of Section 12.5, with 0.05 mm of noise and 1 % of readings lost, stands for it.

> **TECHNOLOGY** **Sensor: Laser Stripe Seam Sensor**
>
> A laser seam sensor projects a stripe of laser light across the joint, a camera images it, and optical triangulation turns the stripe's deformation into the joint's position in three dimensions. The method is common for joints with large grooves, its images are strongly disturbed by the arc, and commercial sensors work at more than 100 mm from the part. It fails where the joint gives the stripe nothing to bend: for a butt joint narrower than 0.2 mm the deformation almost disappears [20]. On a trend a failing sensor shows as missing or jumping readings, which the model's dropouts, noise and covered window stand for.

What Moves It

Two kinds of final element act on the weld. The robot's axes carry the torch and apply the height and lateral corrections, and the feeder and the source set the arc. Modern pulsed sources hold the arc length themselves, comparing the arc voltage with a reference and adjusting the pulse frequency and the current [19]. The feeder lag τ_f of 30 ms and the synergic slope of Equation (12.15) stand for the feeder and the source.



ZY1, ZY2: lateral and height servo axes of the robot, corrections within ±10 mm. SY3: wire feeder, 30 ms lag, 1.5 to 18 m/min. EY4: power source, open-circuit voltage on the synergic line. The travel axis, slowed by the fill law or the guard, is not drawn.

Figure 12.5 The loops of the chapter with real devices in place of the schematic's symbols. ZT1 is the laser stripe sensor ahead of the torch, CT and VT the current and torch-voltage transmitters, ST the feeder tachometer and ZT2 the axis encoders. In the cell controller (dashed frame) the preview buffer feeds the tracking law TC and the fill law, the through-the-arc estimate feeds the height loop HC, and the AVC loop acts on the feed only on a constant-current source. The controller moves the lateral and height axes ZY1 and ZY2, the wire feeder SY3 and the source voltage EY4. Notice that the arc length itself has no loop in the controller: the source and the feeder close it inside the cell.

TECHNOLOGY **Final Element: Power Source and Wire Feeder**

The source and the feeder set the arc between them. A constant-voltage source with a fixed feed holds the arc length by self-regulation, the most common method, while a constant-current source needs a feed motor driven by the process voltage [21]. A pulsed source typically needs a feedback loop in the feeder to follow changes of the distance [18]. In one laboratory cell the current regulator followed its command up to 500 Hz and the capstan feeder only up to 7 Hz [21]. Debris in the contact tube makes the feed hesitate and then stop [18], and a wire that stops lets the arc burn back toward the tip.

Where the Controller Runs

The cell controller of this chapter runs every 20 ms, forty physics steps, while the arc's own loop needs no controller at all. In discrete manufacturing a supervisor for each cell may coordinate a machine controller and a robot controller, and such loops run with cycle times from milliseconds to minutes [22]. An adaptive welding cell joins a six-axis robot, a welding power source and a camera through a process controller that combines the three, and it adjusts the travel speed, the torch orientation and the synergic settings of the source [9]. The preview buffer, the fill law and the window guard of this chapter sit in that cell layer, above the axis servos and beside the source's own regulator.

IN PRACTICE **The Contact Tube Wears Out**

The contact tube is a copper-alloy part with a bore 0.2 to 0.5 mm larger than the wire, and it wears in service. As it wears, the point where current passes into the wire moves, the length of wire carrying current changes, and the arc grows unstable. That instability sets the interval at which the tube is replaced. A welder compensates by moving the gun and spots a worn tube by sight and sound, so an automated cell needs a monitor: in tests at NIST the power of the circuit voltage between 0 and 4 Hz correlated with the wear [18]. The model's contact tip keeps a fixed resistance.

What Is Modernizing It

Cameras now watch the weld pool itself: one adaptive cell measures the pool's width and the position of its front in real time and turns their changes into an adjustment of the process [9]. Deep learning is applied to the monitoring of welding and to predicting weld quality, and a laser vision sensor with deep neural networks has predicted the internal bead shape and the tensile strength of a joint from its external bead shape and the welding conditions [23].

12.8 Limitations

Pulsed, short-circuit and globular transfer, inverter waveform control, arm kinematics and image processing are outside the model, as its assumptions state, and the bead correlations, defect rules, wall rise and drift law are illustrative teaching values rather than a qualified procedure or a distortion model. The through-the-arc lateral calibration is fixed at 3 Hz and reads a 0.3 mm offset 0.54 to 0.78 times at 2 Hz and 1.25 to 1.32 times at 4 Hz. The through-the-arc height is an inversion of the steady arc and is biased and noisy during a transient. The part, the gap and the noise come from one seed, so a case started the same way repeats exactly, which makes comparisons exact and removes the variation a cell sees from part to part, while worst offsets that differ by less than their spread over other seeds do not rank two configurations.

OPEN CHALLENGE **Welding a Joint That Changes Under the Torch**

Distortion, varying seam preparation and a gap that changes during welding remain a major challenge for automated gas metal arc welding. A human welder adjusts speed and torch angle on the fly, while a robot needs sensors to detect the change and actuators to answer it [9]. Models learned from data need data of high quality, and data on unstable welds are scarce in low-volume work on complex paths, where a misjudged weld is costly. Progress would be a cell that adapts from little data, as a framework that adds physical laws to a learned model begins to do [24].

12.9 Conclusion

This chapter studied a robotic arc welding cell that holds its arc length without a controller and reads its seam with a sensor that leads the arc in distance rather than time, in a simulator that logs the true arc, seam and bead beside the cell's measurements. A 3 mm plate step drives the current to 316.5 A and the arc recovers 90 % of its length in 97.0 ms, against 104.7 ms from a linearization of the model, while a constant-current arc stays 0.99 mm long until its voltage-controlled feed restores it in 834.5 ms. The 20.5 A the arc keeps is a height signal that holds the CTWD within 0.13 mm of its setpoint as the plate rises 4 mm, and at a 3 Hz weave the current's sensitivity to the distance is 2.77 times its steady value, close to the 2.5 that the weaving tracker carries. A look-ahead configured 20 mm short turns a 3.5 mm bend into a 1.451 mm error against the 1.455 mm of the geometric law and 372 mm without fusion. The graded seam improves from 1198 mm defective to none at 12.30 mm/s. The models of transfer, bead and distortion are simplified and their limits illustrative. A fuller model would add short-circuit and pulsed transfer, arm kinematics with a sensor interface delay, a laser with image processing, and a bead model fitted to a qualified procedure. The welding

cell gives a student, in a browser, a process that closes its own loop and a sensor whose readings belong to places rather than to moments.

KEY POINTS

- A welding arc holds its own length: a shorter arc draws more current, which melts the wire faster until the arc is long again.
- After a 3 mm plate step the arc recovers 90 % of its length in 97.0 ms, while a constant-current arc stays 0.99 mm long.
- The 20.5 A the arc keeps is a height signal that holds the CTWD within 0.13 mm of its setpoint as the plate rises 4 mm.
- A look-ahead configured 20 mm short turns a 3.5 mm bend into a 1.451 mm error and 372 mm without fusion.
- On a wider gap, the extra metal of adaptive fill brings extra heat.

Where else this applies. Readings filed by place also steer the road-preview suspension of Volume 7, Chapter 11, and a feedforward bounded by the plant also doses the coagulant of Volume 3, Chapter 6.

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12.10 Exercises

12.1 ⌕ Concept check · 2 min

In case 1 the torch meets a 3 mm plate step in MANUAL on the constant-voltage source, with the feed fixed at 8 m/min and no loop acting. The arc is suddenly 1.28 mm long and is 90 % restored 97.0 ms later. What restores it?

(a) The height loop raises the torch, because the current has risen above its reference

(b) The shorter arc draws more current, which melts the wire faster than it is fed

(c) The feeder slows the wire, because the synergic line follows the falling torch voltage

(d) The droplets detach more often at the higher current, and each detachment lengthens the arc

12.2 ⌕ Concept check · 1 min

In case 4 the laser sits 40 mm ahead of the arc, and the controller files its readings as if it sat 20 mm ahead. The seam bends 3.5 mm to either side every 300 mm. Where along the bend is the bead farthest from the seam?

(a) At the crests of the bend, where the seam changes direction fastest

(b) Equally everywhere, since every reading is used the same 20 mm early

(c) Where the seam crosses the taught path, at its steepest slope

(d) Only near the start, until the buffer has filled with readings

12.3 ⌕ Concept check · 2 min

In case 6 the part bows as it heats, and its far end moves 8.36 mm over the weld while the torch weaves 1.5 mm. Laser tracking alone leaves a worst bead offset of 0.380 mm, tracking through the arc alone 0.233 mm, and the laser with the through-the-arc trim 0.154 mm. Which statement explains the ranking?

(a) The laser's noise is larger than the current's, so any arc reading improves its estimate

(b) The trim corrects the configured look-ahead, which the drift has moved off the mounted distance

(c) The weave widens the bead, so the same lateral error counts for less at the groove edges

(d) Each laser reading is 4 s old when the torch arrives, and the trim reads the groove at the torch

12.4 Theory and calculation · 9 min

At the default arc the current is $i = 251.9\,\mathrm{A}$, the extension $l_s = 10.73\,\mathrm{mm}$ and the circuit resistance $R_\Sigma = 47.7\,\mathrm{m\Omega}$. The melting coefficients are $k_1 = 0.300\,\mathrm{mm/(s\,A)}$ and $k_2 = 8.48 \times 10^{-5}\,1/(\mathrm{s\,A^2})$, the column gradient is $E_a = 1.2\,\mathrm{V/mm}$ and the hot wire has $r_w = 0.62\,\mathrm{m\Omega/mm}$.

(a) Compute the arc's share and the extension's share of λ in Equation (12.9), and λ itself. *Checkpoint:* $16.6\,\mathrm{s^{-1}}$ and $5.38\,\mathrm{s^{-1}}$, so $\lambda = 22.0\,\mathrm{s^{-1}}$.

(b) Compute the time constant of self-regulation and the time to 90 % of a step. The full model restores 90 % of the case 1 step in 97.0 ms. Give one reason the model is faster than the linearization. *Checkpoint:* $\tau_{sr} = 45.5\,\mathrm{ms}$ and $2.303\,\tau_{sr} = 104.7\,\mathrm{ms}$.

(c) From Equation (12.10), compute the current's sensitivity to the CTWD at steady state and at a 3 Hz weave, and their ratio. Compare the ratio with the calibration $c = 2.5$ of Equation (12.14). *Checkpoint:* 6.16 A and 17.0 A per millimeter, a ratio of 2.77.

12.5 Theory and calculation · 6 min

Case 4 bends the seam with amplitude $A_b = 3.5\,\mathrm{mm}$ and wavelength $\lambda_b = 300\,\mathrm{mm}$, and the laser is mounted at $d_{la} = 40\,\mathrm{mm}$. The default bead is $w = 8.03\,\mathrm{mm}$ wide, the root gap is 1.0 mm, the groove's top width is $W_V + g$ with $W_V = 4\,\mathrm{mm}$, and the edge margin is $m_e = 0.3\,\mathrm{mm}$.

(a) Use Equation (12.13) to compute the worst lateral error for configured look-aheads of 20, 30, 50 and 60 mm. *Checkpoint:* 1.455, 0.732, 0.732 and 1.455 mm.

(b) Compute the largest bead offset that still fuses both groove edges, and say which of the four configurations the law predicts will lose fusion. *Checkpoint:* 1.22 mm. The 20 and 60 mm configurations.

(c) How far may the configured look-ahead be from the mounted one before the law predicts lack of fusion? Give the answer to 0.1 mm. *Checkpoint:* 16.7 mm, so from about 23.3 to 56.7 mm.

12.6 Theory and calculation · 7 min

In case 8 the travel speed rises from 10 to 14 mm/s with the feed at 8 m/min and the source unchanged. At 10 mm/s the pool's heat input is 681 J/mm. The correlations are $p = a_p H^{b_p}(1 + \beta_g g)$ with $a_p = 0.04184$, $b_p = 0.70$, $\beta_g = 0.05\,\mathrm{mm^{-1}}$ and no weave, a fusion limit $p_{min} = 3.4\,\mathrm{mm}$, an undercut speed $v_{max} = v_u(H/675\,\mathrm{J/mm})^{e_u}$ with $v_u = 13\,\mathrm{mm/s}$ and $e_u = 0.8$, and a deposit $\eta A_w WFS/v$ with $\eta = 0.97$ and 1.2 mm wire. The root gap is 1.0 mm, so the groove needs $12.0\,\mathrm{mm^2}$ per millimeter.

(a) Assume the arc's power does not change with the speed, and compute the heat input at 14 mm/s. *Checkpoint:* 486 J/mm.

(b) Compute the penetration and the undercut speed at that heat input. *Checkpoint:* 3.34 mm and 10.0 mm/s.

(c) Compute the deposit per millimeter at 14 mm/s, and list every defect the bead rules predict. *Checkpoint:* $10.4\,\mathrm{mm^2}$. Lack of fusion, undercut and underfill.

12.7 App challenge · 8 min

Load scenario 1, The arc regulates itself. It runs in MANUAL on the Arc view at the default seed, and the torch meets the 3 mm plate step at 6.95 s. Run each part at 1×, export the CSV, and read the columns `arc_length_mm`, `current_A` and `wfs_mpm` in the rows named. Read the arc length to ±0.05 mm, the current to ±3 A, since the droplets ripple it, and the feed to ±0.05 m/min.

(a) Run the scenario as loaded to 8 s. Read the arc length and the current at 6.90 s and at 7.90 s, and say how much of the 3 mm step the arc does not recover. *Checkpoint:* 4.29 mm and 252 A, then 3.81 mm and 272 A; the arc stays about 0.48 mm shorter.

(b) Reload the scenario with the reload button, set Power source to Constant current before Run, stay in MANUAL, and run to 8 s. Read the arc length at 6.90 s and at 7.90 s. *Checkpoint:* 3.99 mm and 0.99 mm.

(c) Reload, set Power source to Constant current, switch the header to Auto before Run so the AVC loop sets the feed, and run to 9 s. Read the arc length and the feed at 8.90 s, each to ± 0.1, since the slow integral leaves both still moving. *Checkpoint:* 4.44 mm and 6.88 m/min.

12.8 App challenge · 9 min

Load scenario 4, The look-ahead set wrong. It tracks with the laser, which is mounted 40 mm ahead of the arc, and the look-ahead is configured at 20 mm. Use the default seed and run at $2\times$ until the run stops itself when the crater is filled, about 122 s of simulated time. Reload the scenario with the reload button before each part, and make the change before Run. Read the scorecard tiles Worst lateral error and Defects. Worst lateral error is exact to the 0.01 mm the tile shows at the default seed.

(a) Run the scenario as loaded. *Checkpoint:* 1.45 mm; Defects 372 mm, lack of fusion.

(b) Set Look-ahead distance (configured) to 30 mm and run. *Checkpoint:* 0.73 mm; Defects 0 mm.

(c) Set Look-ahead distance (configured) to 60 mm and run. Compare the three results with Equation (12.13), and say which error the law underestimates. *Checkpoint:* 1.49 mm; Defects 397 mm, lack of fusion.

12.9 App challenge · 8 min

Load the challenge, “a 1.2 m seam at 12 mm/s”. It welds at 12.5 mm/s over a gap that varies between 0.8 and 2.2 mm, on a part set 1 mm off its path that drifts as it heats. Use the default seed and run at $2\times$ until the run stops itself when the crater is filled, about 98 s of simulated time. Reload the scenario with the reload button before each part, make every change before Run, and read the tiles Defects, Worst lateral error, Average speed and Wire used.

(a) Set Seam tracking to Laser, Adaptive fill On with Fill by on Wire feed, Wire feed speed (CV) to 10.0 m/min, Source voltage (open circuit) to 34.2 V and Reinforcement target to 1.0 mm^2, and run. *Checkpoint:* Defects 0 mm, 0.13 mm, 12.3 mm/s, 18.1 m; the challenge target is met.

(b) Make the same changes but leave the feed at 8.0 m/min and the source at 31.8 V, and run. *Checkpoint:* Defects 331 mm, undercut; 0.13 mm, 12.3 mm/s, 17.2 m.

(c) Explain part (b) with the undercut correlation of Equation (12.8), taking the heat input of the 8 m/min procedure at 12.5 mm/s as 681 J/mm scaled by the speed. *Checkpoint:* 545 J/mm, an undercut speed of 10.9 mm/s.

12.10 Application area · 3 min

A shielding-gas loss in case 7 at 45 s trips the flow switch 0.28 s later, and the supervisor stops the weld at 443 mm, leaving 8 mm of porous, unfilled crater. With the gas stop off, 760 mm of the seam are porous.

(a) Which setting should a production cell use, and what does the repair cost in each case? *Checkpoint:* Stop on gas loss; a crater to repair against most of the seam.

(b) Why does the monitor wait for the flow to stay below 70 % for 0.3 s instead of stopping at the first low reading? *Checkpoint:* The flow switch is noisy, and a short dip does not spoil the shield.

12.11 Application area · 3 min

A technician replaces a bent laser bracket with a longer one that mounts the scanner 60 mm ahead of the arc, and nobody changes the configured look-ahead of 40 mm. The cell is checked by welding a straight test coupon whose seam is offset 2 mm from the taught path, and it passes.

(a) What does Equation (12.13) predict on the coupon, and on production parts that bend like case 4? *Checkpoint:* No error on the straight coupon; 1.455 mm on the bend.

(b) How can the fault be found before a bead shows it? *Checkpoint:* Compare where the readings are filed with where the laser line falls, or weld a known feature.

12.12 Review the agent · 5 min

An AI assistant reviews case 5 and writes: “Fill by wire feed welds the whole seam sound as the gap opens from 1.0 to 2.1 mm, because the law adds exactly the wire the measured gap needs. The law has no limit except the feeder’s 18 m/min, so the same settings will weld parts whose gap opens to 2.5 mm. Set the Root gap slider to 1.4 mm and expect a sound seam.” Find the flaw, and say how you would check the claim in the application.