# SeamLess: Bridging the Machine Gap in Personal Fabrication

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## Abstract

Manufacturing objects often involves several different materials and production machines. Intermediate products have to be physically transferred from one machine to the next and properly aligned for the next production step. With *SeamLess*, we introduce an implementation of a holistic approach to personal fabrication that helps makers bridge this machine gap. Our open-source software implements an example workflow between laser cutting, 3D printing, textile embroidery, and electronics. It adds information to machine files that creates alignment guides on the fabricated parts and machines themselves. In a workshop, *SeamLess* had a significant positive impact on bridging the machine gap without impacting existing maker processes.

## CCS Concepts

• **Human-centered computing → Human computer interaction (HCI)**; **HCI theory, concepts and models**.

## Keywords

personal fabrication, tools, design, interoperability

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## 1 Introduction

Manufacturing even a simple item is usually heterogeneous in nature, involving multiple different materials, machines, and production steps. Bridging this *machine gap* requires planning how intermediate results move from one production machine to the next.

Personal fabrication has brought manufacturing to a much broader public through education [Praveena et al. 2022], and through open workshops such as Fablabs[1]. However, unlike professional manufacturing, it is usually concerned with the making of one-off or low-volume items, by novices or amateurs. Often, the product has to be handed over to another person who knows the next machine well enough to operate it [Goveia da Rocha et al. 2021]. These enforced context switches are error-prone and increase the barrier of entry. This makes bridging the machine gap one of the key challenges in any personal fabrication project that involves more than one machine.

We present *SeamLess*, a software-supported workflow[2] that allows makers to move their project from one machine to the next without losing the individual expressiveness of the respective tools themselves. *SeamLess* generates all the machine files at once and adds alignment guides for the whole process to these files. The result is a sequential list of actions to be performed, eliminating the problems that arise from manual alignment.

We validated *SeamLess* in a workshop with 12 makers. Our results show that *SeamLess* made moving between machines easy, quick, and precise, thus lowering the entry barrier into personal fabrication.

## 2 Related Work

Compared to professional manufacturing, personal fabrication is generally interested in fast results, rapid iterative improvements, and often a one-time process. This has made the turnaround and iteration time to fabricate prototypes of an object an important factor in research [Mueller et al. 2014]. Solutions to this problem often combine or substitute other materials, including building blocks (bricks) [Mueller et al. 2014] or laser-cut wood [Beyer et al. 2015]. This integrates other workflows with 3D printing and requires manual assembly.

An important aspect of personal fabrication is the expressive range that makers can achieve with the machines available to them. With the prevalence of sewing machines, the use of textiles in 3D printing has received considerable attention in research. These include using textiles as surfaces [Rivera et al. 2017], leveraging the elasticity [Goudswaard et al. 2020], the possibility of (conductive) embroidery [Gilliland et al. 2010], creating heating elements [Šahta et al. 2014], or hidden displays [Olwal and Dementyev 2022].

The move to include more materials and machines raises the barrier to entry into personal fabrication, which benefits from being

[1]https://www.fablabs.io/
[2]https://www.hci.rwth-aachen.de/seamless


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as accessible as possible. Goveia da Rocha et al. identified the need for guidelines that coordinate workflows between machines and called for a holistic approach to fabrication [Goveia da Rocha et al. 2021]. *SeamLess* is concerned with alignment steps in personal fabrication and therefore has the potential to integrate with fabrication processes that use embeddings.

# 3 Workflow

With *SeamLess* the fabrication process starts with the 3D printer printing alignment studs onto the print bed (Fig. 1c). At the same time, the embroidery machine embroiders our textile, adding cutting lines and reinforcements in the alignment areas (Fig. 1a). The finished embroidery is moved onto a wooden sheet in the laser cutter. Aligning the rigid frame with the rigid wooden sheet in the laser cutter is achieved by moving both to the same corner of the cutting area (Fig. 1b). The laser cutter then cuts out the areas (in textile and wood) that the studs must pass through. The prepared textile is then clipped onto the studs in the 3D printer, to print a wireframe structure directly onto the fabric (Fig. 1d). The alignment studs now fit into the holes in the wooden sheet and align the fabric with the 3D print on the laser cutter (Fig. 1e). The laser cutter now removes excess textile by cutting along the borders (Fig. 1f). The *SeamLess* fabrication workflow steps are independent of the fabricated object.

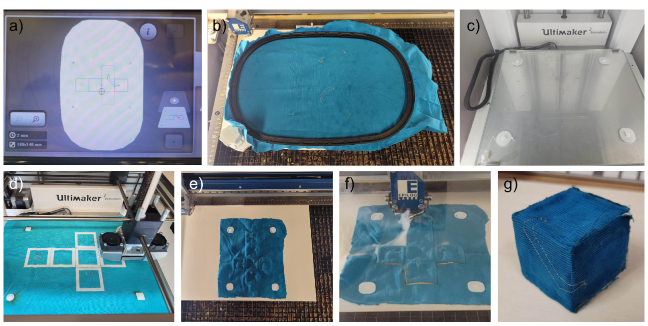


**Figure 1: The workflow on the example of a cube with conductive traces: a) the embroidery step; b) the alignment of the embroidery assembly on a wood sheet in the laser cutter; c) the 3D print of the alignment studs on the print bed; d) the 3D printing of the structural wireframe onto the aligned textile; e) the alignment of the 3D print onto the wood sheet in the laser cutter; f) the removal of excess material with the laser cutter; g) the finalized object.**

# 4 Workshop

We validated our *SeamLess* workflow and software tool in a workshop in our lab with six groups of two participants each.

Our lab provided an UltiMaker S3 Extended[3] with UltiMaker Cura[4], an Epilog Fusion M2 40[5] with Epilog Dashboard, a Bernina 880[6], and TinkerCAD[7]. Before the workshop participants consented to data collection, completed a demographic survey, and estimated their skill level in the use of the required tools. The workshop was split into an introduction phase and a workflow phase and ended with a post-test questionnaire based on the System Usability Scale (SUS) [Brooke 1996].

The introduction phase started with an explanation of 3D design software, continued with embroidery, the laser cutter, and finally the 3D printer. Then, we guided the participants through all personal fabrication methods with predetermined intermediate objects, which resulted in the creation of one full object. After each step, we asked participants to complete a questionnaire concerning their perception of the previous fabrication step and the switch between the fabrication steps to determine a baseline for the workflow phase.

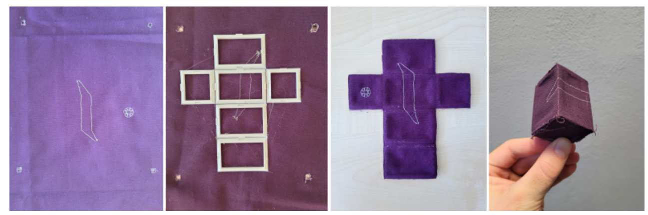

**Figure 2: The object our participants built in several fabrication steps in the workshop. From left to right: the embroidered textile with alignment markings in the corners, the 3D-printed backside with cut-out alignment holes, the final unassembled part, and the resulting object.**

The workflow phase started with an explanation of the *SeamLess* process. The participants then designed their own objects by sketching ideas on paper before modeling them in TinkerCAD. Afterwards, participants went through the fabrication steps of a pre-determined object (shown in Fig.2) in the order given by the *SeamLess* workflow. After each step, the participants completed the same questionnaires as in the introduction phase.

# 5 Results and Discussion

We recruited 12 participants (6 male, 5 female, 1 diverse) into 6 groups of 2. Ages ranged from 19 to 32, with a mean of 24.9 years. 7 participants came from computer science, 4 from engineering, and 1 participant from the design field. Except for P1 and P11, none had experience in personal fabrication.

Throughout the workshop our participants designed 45 objects, with 30 including conductive embroidered traces. Popular concepts among these were lamps, furniture, toys, interfaces, decoration, storage, costumes, and miniatures.

Participants were asked to rate their experience in two general categories. First, the use of machinery with respect to *ease*, *success*, and *confidence*. Second, alignment of partial fabrications on a machine with respect to *ease*, *precision*, and *time*. These questions were rated on a 7-point Likert scale, with space available for textual comments. These comments were translated into English.

[3]https://ultimaker.com/3d-printers/s-series/ultimaker-s3/
[4]https://ultimaker.com/software/ultimaker-cura/
[5]https://www.epiloglaser.com/laser-machines/legacy-systems/fusion-m2-32-40/
[6]https://www.bernina.com/en-US/Machines-US/Series-Overview/BERNINA-8-Series/BERNINA-880
[7]https://www.tinkercad.com/

Our distribution test showed that the data were ordinal. Significance testing was performed using nonparametric Wilcoxon tests with $\alpha = 0.05$.

The embroidery step did not change between the introduction and workflow phases. This shows that repetition of one step alone does not significantly change perceived ease *(m=0.75, w=3, p=0.0053)*, success *(m=0.25, w=3, p=0.18)*, and confidence *(m=0.42, w=8, p=0.13)*.

The use of the laser cutter did not change significantly. However, it significantly increased in how easy *(m=1.67, w=5, p=0.02*)*, precise *(m=1.5, w=6.0, p=0.03*)*, and quickly *(m=1.92, w=5, p=0.02*)* alignment felt. P9 mentioned that "positioning is clear by the grid in the software and the coordinates on the machine".

The use of the 3D printer did not change significantly. However, it significantly increased in how easy *(m=2.42, w=2, p=0.009*)*, precise *(m=2.5, w=5, p=0.005*)*, and quickly *(m=2.25, w=0, p=0.0005*)* alignment felt. This contrast is supported by the difference in comments without *SeamLess* ("[...] positioning on the plate [physically] seems challenging [...]" (P4)) and with ("It is difficult to make any mistakes" (P9)).

The use of the laser cutter was significantly impacted in the perception of ease *(m=1.5, w=5, p=0.01*)*. *SeamLess* significantly increased how easy *(m=2.01, w=2, p=0.009*)*, and quickly *(m=2.33, w=4.0, p=0.009*)* alignment felt. Precision was not significantly affected. P3 liked "being able to use the studs from printing again".

The SUS results were interpreted on a 7-point scale [Dawes 2008; Finstad 2010]. *SeamLess* achieved a slightly below average SUS score of 66.2.

## 6 Conclusion & Future Work

*SeamLess* introduces a workflow that automatically bridges the manual machine gap existing in personal fabrication. Inspired by the results of Goveia da Rocha et al. [Goveia da Rocha et al. 2021], we built a multi-step workflow to create a textile-covered 3D object. Our software automatically generates guides that make part alignment across machines easy, fast, and precise. We evaluated *SeamLess* in a workshop with 12 participants to understand how the reduction of manual alignment work affected the fabrication process. Despite adding additional steps and even new machines to the process, alignment became significantly quicker, simpler, and more precise. The study also revealed a slightly below-average SUS score for the prototypical workflow, probably caused by the generally poor usability of the individual machines. Overall, our results show that a holistic approach to inter-machine workflows holds much promise.

*SeamLess* currently supports a particular fabrication process. However, the underlying concept is key and we expect it to scale well. An example generalization could be the addition of routing conductive traces through not only conductive yarn but also conductive filament [Kwok et al. 2017]. Specialized maker-friendly machines that integrate multiple processes can further help on this path by reducing the need to move between machines [Rivera and Hudson 2019; Weichel et al. 2015].

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