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# AN ANALYSIS OF A CLASS OF VARIATIONAL MULTISCALE METHODS BASED ON SUBSPACE DECOMPOSITION

RALF KORNHUBER, DANIEL PETERSEIM, AND HARRY YSERENTANT

ABSTRACT. Numerical homogenization tries to approximate the solutions of elliptic partial differential equations with strongly oscillating coefficients by functions from modified finite element spaces. We present a class of such methods that are closely related to the methods that have recently been proposed by Målqvist and Peterseim [Math. Comp. 83, 2014, pp. 2583–2603]. Like these methods, the new methods do not make explicit or implicit use of a scale separation. Their comparatively simple analysis is based on the theory of additive Schwarz or subspace decomposition methods.

## 1. INTRODUCTION

Numerical homogenization aims at a modification of standard finite element discretizations that preserve the accuracy known from smooth coefficient functions to the case of highly oscillatory coefficient functions. A method of this kind, which utilizes no separation of scales at all and is founded on a comprehensive convergence theory, has recently been proposed by Målqvist and one of the authors [10]. The central idea of this paper, which can be considered as a late descendant of the work of Babuška and Osborn [1], is to assign to the vertices of the finite elements new basis functions that span the modified finite element space and reflect the multiscale structure of the problem under consideration. In the basic version of the method, the new basis functions are the standard piecewise linear hat functions minus their orthogonal projection onto a space of rapidly oscillating functions, orthogonal with respect to the symmetric, coercive bilinear form associated with the boundary value problem. They possess a global support but decay exponentially from one shell of elements surrounding the assigned vertex to the next. It is therefore possible to replace them by local counterparts without sacrificing the accuracy. The support of these localized basis functions consists of a fixed number of shells of elements surrounding the associated node. The number of these shells increases logarithmically with increasing accuracy, that is, decreasing gridsize.

Here we present a considerably simplified analysis of a class of closely related methods that is based on the theory of iterative methods, more precisely of additive Schwarz or subspace decomposition methods [13], [15], and essentially utilizes a reinterpretation [12] of the method proposed in [10] in terms of variational multiscale methods. Arguments used in the present paper are inspired by the work of Demko [5] on the inverses of band matrices and have been used, for example, in the proof of the  $H^1$ -stability of the  $L_2$ -orthogonal projection onto finite element spaces [2]. Our proof works on a more abstract level than that in [10] and is less

centered around the single finite element basis functions. Implicitly, it compares their projections onto the mentioned space of rapidly oscillating functions with their iteratively calculated approximations and shows in this way that these decay exponentially with the distance to the assigned nodes. It rests, as that of all related results, upon a local version of the Poincaré inequality and thus depends on the local contrast ratio. A different class of methods not suffering from such restrictions and condensing, similar to numerical homogenization methods, the features of the problem under consideration in a relatively low dimensional matrix can possibly be based on hierarchical matrices [7]; see the recent work of Bebendorf [3] in conjunction with the work of Hackbusch and Drechsler [8].

The present paper builds a bridge between numerical homogenization methods and multigrid-like iterative solvers. As a matter of fact, many numerical upscaling techniques bear close and often overlooked resemblance to techniques used by the multigrid community to develop fast iterative methods suitable for problems with rough coefficient functions. A prominent example of this kind, not unsimilar to our approach, is the technique used by Xu and Zikatanov [14] to construct coarse-level basis functions for algebraic multigrid methods; another is the reference [9], in which the direct application of a two-grid iterative method to numerical homogenization is studied and compared to methods like ours.

## 2. THE EQUATION AND THE BASIC APPROXIMATION OF ITS SOLUTIONS

The model problem considered in this paper is a standard second order differential equation in weak form with homogeneous Dirichlet boundary conditions on a polygonal domain  $\Omega$  in  $d = 2$  or  $3$  space dimensions. Its solution space is the Sobolev space  $H_0^1(\Omega)$  and the associated bilinear form reads

$$(2.1) \quad a(u, v) = \int_{\Omega} \nabla u \cdot A \nabla v \, dx.$$

The matrix  $A$  is a function of the spatial variable  $x$  with measurable entries and is assumed to be symmetric positive definite. We assume for simplicity that

$$(2.2) \quad \delta |\eta|^2 \leq \eta \cdot A(x) \eta \leq M |\eta|^2$$

holds for all  $\eta \in \mathbb{R}^d$  and almost all  $x \in \Omega$ , where  $|\eta|$  denotes the euclidean norm of  $\eta$  and  $\delta$  and  $M$  are positive constants. In the same way as in [9] it is possible to replace this condition by an, at least in the quantitative sense, weaker local condition on the contrast ratio. The condition (2.2) guarantees that the bilinear form (2.1) is an inner product on  $H_0^1(\Omega)$ . It induces the energy norm  $\|\cdot\|$ , which is equivalent to the original norm on this space. The boundary value problem

$$(2.3) \quad a(u, v) = f^*(v), \quad v \in H_0^1(\Omega),$$

possesses by the Lax-Milgram theorem under the condition (2.2) for all bounded linear functionals  $f^*$  on  $H_0^1(\Omega)$  a unique solution  $u \in H_0^1(\Omega)$ .

We cover the domain  $\Omega$  with a triangulation  $\mathcal{T}$ , consisting of triangles in two and of tetrahedrons in three space dimensions. We assume that the elements in  $\mathcal{T}$  are shape regular but do not require that  $\mathcal{T}$  is quasiuniform. Associated with  $\mathcal{T}$  is the conforming, piecewise linear finite element subspace  $\mathcal{S}$  of  $H_0^1(\Omega)$ . A key ingredient of the methods discussed here is a bounded local linear projection operator

$$(2.4) \quad \Pi : H_0^1(\Omega) \rightarrow \mathcal{S} : u \rightarrow \Pi u$$

like that defined as follows. At first, the given function  $u \in H_0^1(\Omega)$  is locally, on the single elements  $t \in \mathcal{T}$ , approximated by its  $L_2$ -orthogonal projection onto the space of linear functions, regardless of the continuity across the boundaries of the elements. In a second step, the values of these approximants at a vertex in the interior of the domain are replaced by a weighted mean, according to the contribution of the involved elements to the area or the volume of their union. The values at the vertices on the boundary are set to zero. Together, these values fix the projection  $\Pi u$  of  $u$  onto  $\mathcal{S}$ . For functions  $u \in H_0^1(\Omega)$ , then the estimates

$$(2.5) \quad |\Pi u|_1 \leq c_1 |u|_1, \quad \|h^{-1}(u - \Pi u)\|_0 \leq c_2 |u|_1$$

hold, where  $\|\cdot\|_0$  denotes the  $L_2$ -norm,  $|\cdot|_1$  the  $H^1$ -seminorm, and  $h$  is an elementwise constant function whose value on the interior of a given element is its diameter. The first condition means that the projection operator (2.4) is stable with respect to the  $H^1$ -norm and therefore also with respect to the energy norm. The second condition is an approximation property. The constants  $c_1$  and  $c_2$  depend, as with any other reasonable choice of  $\Pi$ , only on the shape regularity of the finite elements, but not on their size. Quasi-interpolation operators are a common tool in finite element theory. The use of quasi-interpolation operators that are at the same time projections onto the finite element space under consideration can be traced back to the work of Brenner [4] and Oswald [11]. The operator described above falls into this category and is analyzed in the appendix to this paper. A comprehensive recent presentation of such constructions can be found in [6].

The kernel  $\mathcal{V} = \ker \Pi$  of  $\Pi$  is a closed subspace of  $H_0^1(\Omega)$  and therefore itself a Hilbert space. We can therefore introduce the  $a$ -orthogonal projection operator  $C$  from  $H_0^1(\Omega)$  onto the kernel of  $\Pi$  and moreover the finite dimensional subspace

$$(2.6) \quad \mathcal{W} = \{v - Cv \mid v \in \mathcal{S}\}$$

of the  $a$ -orthogonal complement of the kernel of  $\Pi$ . The dimension of  $\mathcal{W}$  and of the finite element space  $\mathcal{S}$  coincide as  $v \in \mathcal{S}$  can be recovered from  $v - Cv$  via

$$(2.7) \quad v = \Pi(v - Cv).$$

Analogously to the approach in [10], we discretize the equation (2.3) using  $\mathcal{W}$  both as trial and test space. The following representation of the approximate solution is based on observations made in [12], where a computationally more advantageous nonsymmetric variant with  $\mathcal{S}$  as trial and  $\mathcal{W}$  as test space is advocated.

**Lemma 2.1** (Peterseim [12], cf. also Målqvist and Peterseim [10]). *The equation*

$$(2.8) \quad a(w, \chi) = f^*(\chi), \quad \chi \in \mathcal{W}$$

*possesses a unique solution  $w \in \mathcal{W}$ , namely the projection*

$$(2.9) \quad w = \Pi u - C\Pi u$$

*of the exact solution  $u \in H_0^1(\Omega)$  of equation (2.3) onto the space  $\mathcal{W}$ . The error*

$$(2.10) \quad u - w = Cu$$

*is the  $a$ -orthogonal projection  $Cu$  of the solution  $u$  onto the kernel of  $\Pi$ .*

*Proof.* As  $\Pi$  is a projection operator,  $u - \Pi u$  is contained in the kernel of  $\Pi$ . The difference of the exact solution  $u$  and the function (2.9) can therefore be written as

$$u - w = (u - \Pi u) - C(u - \Pi u) + Cu = Cu.$$

Because the functions in  $\mathcal{W}$  are  $a$ -orthogonal to the functions in the range of  $C$ ,

$$a(u - w, \chi) = 0, \quad \chi \in \mathcal{W},$$

follows. That is, this  $w$  is the unique solution of the equation (2.8).  $\square$

The energy norm of  $Cu$  can easily be estimated for a right-hand side:

$$(2.11) \quad f^*(v) = \int_{\Omega} f v \, dx.$$

One obtains in this way the following, rather surprising error estimate.

**Theorem 2.2** (Målqvist and Peterseim [10]). *For right-hand sides of the form (2.11), the approximate solution (2.9) satisfies the energy norm error estimate*

$$(2.12) \quad \|u - w\| \leq c \|hf\|_0,$$

where the constant  $c$  depends only on the constants  $c_2$  from (2.5) and  $\delta$  from (2.2).

*Proof.* The proof is based on the representation (2.10) of the error as  $a$ -orthogonal projection  $Cu$  of the solution  $u$  onto the kernel of  $\Pi$  and starts from the identity

$$\|Cu\|^2 = a(u, Cu - \Pi Cu) = (f, Cu - \Pi Cu),$$

from which one obtains the estimate

$$\|Cu\|^2 \leq \|hf\|_0 \|h^{-1}(Cu - \Pi Cu)\|_0.$$

The second factor on the right-hand side is estimated with help of the error estimate from (2.5), and the  $H^1$ -seminorm of  $Cu$ , then with (2.2) by its energy norm.  $\square$

Remarkably, neither the smoothness of the solution  $u$  nor the regularity properties of the equation enter into this error estimate. The size of the error bound is determined by the local behavior of the right-hand side  $f$ .

### 3. LOCALIZATION

Let  $x_1, x_2, \dots, x_n$  be the vertices of the elements in the triangulation  $\mathcal{T}$  and let  $\varphi_1, \varphi_2, \dots, \varphi_n$  be the piecewise linear hat functions assigned to these nodes. The  $\varphi_i$  assigned to the nodes in the interior of the domain  $\Omega$  then form a basis of the finite element space  $\mathcal{S}$ , and the corresponding functions  $\varphi_i - C\varphi_i$  a basis of the trial space (2.6). It has been shown in [10] that these basis functions decay exponentially with the distance to the assigned nodes and can therefore be replaced by localized counterparts. We deviate here from the arguments there and utilize the theory of iterative methods to prove a result of similar kind. Let  $\omega_i$  be the union of the finite elements with vertex  $x_i$  and let

$$(3.1) \quad \mathcal{V}_i = \{v - \Pi v \mid v \in H_0^1(\omega_i)\}.$$

The functions in  $\mathcal{V}_i$  vanish outside a small neighborhood of the vertex  $x_i$ , depending on the choice of  $\Pi$ . For the exemplary operator mentioned earlier, this neighborhood consists of the two shells of elements surrounding  $x_i$ . The  $\mathcal{V}_i$  are closed subspaces of the kernel  $\mathcal{V}$  of  $\Pi$ . This can be seen as follows. Let the  $v_k \in \mathcal{V}_i$  converge to the function  $v \in \mathcal{V}$ . As the  $v_k$  are piecewise linear outside  $\omega_i$ , the same holds for  $v$ . Thus there exists a function  $\varphi$  in the finite element space  $\mathcal{S}$  such that  $v - \varphi \in H_0^1(\omega_i)$ . Because  $\Pi v = 0$  and  $\Pi \varphi = \varphi$ , then

$$(3.2) \quad v = (v - \varphi) - \Pi(v - \varphi) \in \mathcal{V}_i.$$

Let  $P_i$  be the  $a$ -orthogonal projection from  $H_0^1(\Omega)$  to  $\mathcal{V}_i$ , defined via the equation

$$(3.3) \quad a(P_i v, v_i) = a(v, v_i), \quad v_i \in \mathcal{V}_i.$$

Introducing the, with respect to the bilinear form (2.1), symmetric operator

$$(3.4) \quad T = P_1 + P_2 + \cdots + P_n,$$

the approximation spaces replacing  $\mathcal{W}$  are built up with the help of the bounded linear operators  $F_\nu$  from  $H_0^1(\Omega)$  to  $\mathcal{V}$  that are, starting from  $F_0 u = 0$ , defined via

$$(3.5) \quad F_{\nu+1} u = F_\nu u + T(u - F_\nu u).$$

The correction  $T(u - F_\nu u)$  is the sum of its components  $d_i = P_i(u - F_\nu u)$  in the subspaces  $\mathcal{V}_i$  of  $\mathcal{V}$ , the solutions  $d_i \in \mathcal{V}_i$  of the local equations

$$(3.6) \quad a(d_i, v_i) = a(u, v_i) - a(F_\nu u, v_i), \quad v_i \in \mathcal{V}_i.$$

The new trial and test spaces are the spaces  $\mathcal{W}_\ell$  spanned by the functions

$$(3.7) \quad \varphi_i - F_\nu \varphi_i, \quad \nu = 0, 1, \dots, \ell,$$

attached to the nodes  $x_i$  in the interior of the domain  $\Omega$ . In contrast to their counterparts  $\varphi_i - C\varphi_i$  spanning the original space  $\mathcal{W}$  they have a local support, which expands layer by layer with the number  $\nu$  of iterations.

To study the approximation properties of these spaces  $\mathcal{W}_\ell$ , we consider optimally or almost optimally chosen fixed linear combinations

$$(3.8) \quad C_\ell = \sum_{\nu=0}^{\ell} \alpha_{\ell\nu} F_\nu, \quad \sum_{\nu=0}^{\ell} \alpha_{\ell\nu} = 1,$$

of the operators  $F_\nu$  as approximations of the  $a$ -orthogonal projection  $C$ . These operators  $C_\ell$  serve here solely as a tool and do not need to be explicitly accessible. Our analysis is based on the theory of additive Schwarz or subspace decomposition methods, here applied to an equation in the kernel  $\mathcal{V}$ . Key is the following lemma.

**Lemma 3.1.** *For all  $v \in \mathcal{V}$ , there is a with respect to the energy norm stable decomposition  $v = v_1 + \cdots + v_n$  of  $v$  into functions  $v_i$  in the spaces  $\mathcal{V}_i$ , such that*

$$(3.9) \quad \sum_{i=1}^n \|v_i\|^2 \leq K_1 \|v\|^2$$

*holds, where the constant  $K_1$  depends only on the constants  $c_1$  and  $c_2$  from (2.5), on the shape regularity of the finite elements, and on the contrast ratio  $M/\delta$ . Moreover, there is a constant  $K_2$  such that*

$$(3.10) \quad \|v\|^2 \leq K_2 \sum_{i=1}^n \|v_i\|^2$$

*holds for all such decompositions of  $v$  into functions  $v_i$  in the subspaces  $\mathcal{V}_i$  of the kernel. This constant depends only on the shape regularity of the finite elements.*

*Proof.* The upper estimate (3.10) is rather trivial because  $K_2$  can be bounded in terms of the maximum number of the parts  $v_i$  that do not vanish on a given element. We use that the  $\varphi_i$  form a partition of unity and prove that (3.9) holds for the decomposition of a function  $v$  in the kernel  $\mathcal{V}$  of  $\Pi$  into the parts

$$v_i = \varphi_i v - \Pi(\varphi_i v), \quad i = 1, \dots, n,$$

in  $\mathcal{V}_i$ . It suffices to prove that this decomposition is  $H^1$ -stable. By the  $H^1$ -stability of the projection  $\Pi$  and the shape regularity of the finite elements one obtains

$$\sum_{i=1}^n |v_i|_1^2 \lesssim \sum_{i=1}^n |\varphi_i v|_1^2 \lesssim |v|_1^2 + \|h^{-1}v\|_0^2.$$

Using once more that  $\Pi v = 0$ , the second term on the right-hand side can, by the approximation property from (2.5), be estimated as

$$\|h^{-1}v\|_0 = \|h^{-1}(v - \Pi v)\|_0 \lesssim |v|_1.$$

Since the  $H^1$ -seminorm can, because of the assumption (2.2), be estimated by the energy norm and vice versa, the estimate (3.9) follows and the proof is complete.  $\square$

With the help of the estimates (3.9) and (3.10) one can show that

$$(3.11) \quad 1/K_1 a(v, v) \leq a(Tv, v) \leq K_2 a(v, v)$$

holds for the functions  $v$  in the kernel  $\mathcal{V}$  of  $\Pi$ . The spectrum of  $T$ , seen as an operator from  $\mathcal{V}$  to itself, is therefore a compact subset of the interval with the endpoints  $1/K_1$  and  $K_2$ . Because  $I - F_\nu = (I - T)^\nu$  and  $F_\nu C = F_\nu$ ,

$$(3.12) \quad C - C_\ell = \left\{ \sum_{\nu=0}^{\ell} \alpha_{\ell\nu} (I - T)^\nu \right\} C.$$

Using the spectral mapping theorem and the fact that the norm of a bounded, symmetric operator from a Hilbert space to itself is equal to its spectral radius, one gets therefore, similarly to the finite dimensional case, the following error estimate.

**Lemma 3.2.** *If the weights  $\alpha_{\ell\nu}$  are optimally chosen, the estimate*

$$(3.13) \quad \|Cu - C_\ell u\| \leq \frac{2q^\ell}{1 + q^{2\ell}} \|Cu\|$$

holds for all  $u \in H_0^1(\Omega)$ , where the convergence rate

$$(3.14) \quad q = \frac{\sqrt{\kappa} - 1}{\sqrt{\kappa} + 1}$$

is determined by the condition number  $\kappa \leq K_1 K_2$  of the operator (3.4) seen as bounded, symmetric operator from the subspace  $\mathcal{V}$  of  $H_0^1(\Omega)$  to itself.

The distance of  $C_\ell u$  to  $Cu$  can thus be estimated in terms of the two constants  $K_1$  and  $K_2$  and the norm of  $Cu$  and tends exponentially in the number  $\ell$  of iterations to zero. The lemma is basically a reformulation of a standard result from the theory of subspace decomposition methods [13], [15], where  $Cu$  is here the solution of the equation and the  $C_\ell u$  are its iteratively generated approximations. We refer to [9] for the missing details of the here only sketched proof.

**Theorem 3.3.** *Let  $w$  and  $w_\ell$  be the best approximations of the solution  $u$  of the original equation (2.3) in  $\mathcal{W}$  and  $\mathcal{W}_\ell$  with respect to the energy norm. Then*

$$(3.15) \quad \|u - w_\ell\| \leq \left( 1 + \frac{2q^\ell}{1 + q^{2\ell}} \right) \|u - w\| + \frac{2q^\ell}{1 + q^{2\ell}} \|u - \Pi u\|.$$

*Proof.* Because  $w_\ell$  is the best approximation of  $u$  by a function in  $\mathcal{W}_\ell$ , because the function  $\Pi u - C_\ell \Pi u$  is contained in this space, and because  $w = \Pi u - C \Pi u$ , we have

$$\|u - w_\ell\| \leq \|u - (\Pi u - C_\ell \Pi u)\| = \|(u - w) - (C \Pi u - C_\ell \Pi u)\|.$$

The distance of  $C \Pi u$  and  $C_\ell \Pi u$  can according to Lemma 3.2 be estimated by the energy norm of  $C \Pi u$ . As  $C \Pi u = (u - w) - (u - \Pi u)$ , this leads to (3.15).  $\square$

We conclude that logarithmically many iteration steps  $\nu$  or even less, depending on the behavior of the energy norm of  $u - \Pi u$ , suffice to reach the same level of accuracy as with the original space  $\mathcal{W}$  based on the exact projection  $C$ . The best approximation  $w_\ell$  of the solution  $u$  in the space  $\mathcal{W}_\ell$  can itself again be calculated iteratively by an additive or multiplicative Schwarz or subspace decomposition method based on the splitting of  $\mathcal{W}_\ell$  into the finite element space  $\mathcal{S}$ , that provides for the global exchange of information, and local subspaces like

$$(3.16) \quad \mathcal{W}_{\ell,i} = \text{span}\{\varphi_i - F_\nu \varphi_i \mid \nu = 0, \dots, \ell\},$$

bearing the information on the fine scale structure of the solution.

The proof of Theorem 3.3 shows that one can replace the  $\ell + 1$  functions (3.7) attached to the nodes  $x_i$  in the interior of  $\Omega$  by a single, fixed linear combination

$$(3.17) \quad \sum_{\nu=0}^{\ell} \alpha_{\ell\nu} (\varphi_i - F_\nu \varphi_i), \quad \sum_{\nu=0}^{\ell} \alpha_{\ell\nu} = 1,$$

without sacrificing the error bound (3.15). This considerably reduces the size of the spaces  $\mathcal{W}_\ell$ . The problem is that the optimum coefficients  $\alpha_{\ell\nu}$  depend on the entire spectrum of the operator  $T$  from the kernel  $\mathcal{V}$  to itself. In a much simplified variant, approximations  $C_\ell$  of the projection  $C$  are determined via a recursion

$$(3.18) \quad C_{\ell+1} u = C_\ell u + \omega T(u - C_\ell u),$$

where  $C_0 u = 0$  is set and  $\omega \geq 1/K_2$  is a damping parameter whose optimal value depends again on the endpoints of the spectrum. Because in this case

$$(3.19) \quad C - C_\ell = (I - \omega T)^\ell C,$$

convergence is guaranteed at least for  $\omega < 2/K_2$ , and for  $\omega = 1/K_2$  in particular. The functions  $\varphi_i - C_\ell \varphi_i$  spanning the new spaces  $\mathcal{W}_\ell$  can be calculated in the same way as the functions  $\varphi_i - F_\nu \varphi_i$ . The convergence rate degrades, however, with this version from (3.14) to a value not better than

$$(3.20) \quad q = \frac{\kappa - 1}{\kappa + 1},$$

and in the extreme case to  $q = 1 - 1/(K_1 K_2)$  if  $\omega = 1/K_2$  is chosen. This means that possibly a larger number  $\ell$  of iterations and layers, respectively, is needed.

#### 4. DISCRETIZATION

The infinite dimensional subspaces  $\mathcal{V}_i$  of the kernel of the projection  $\Pi$  have to be replaced by discrete counterparts to obtain a computationally feasible method. We start from a potentially very strong, uniform or nonuniform refinement  $\mathcal{T}'$  of the triangulation  $\mathcal{T}$ , bridging the scales and resolving the oscillations of the coefficient functions, and a finite element space  $\mathcal{S}' \subseteq H_0^1(\Omega)$  that consists of the continuous functions whose restrictions to the elements in  $\mathcal{T}'$  are linear. The whole theory then

literally transfers to the present situation replacing only the continuous solution space  $H_0^1(\Omega)$  and its subspaces by their discrete counterparts. The only modification concerns the construction of the stable decomposition of the functions  $v$  in the kernel of  $\Pi$  into a sum of functions in the corresponding local subspaces

$$(4.1) \quad \mathcal{V}_i = \{v - \Pi v \mid v \in \mathcal{S}' \cap H_0^1(\omega_i)\}.$$

To construct such a decomposition, we use the interpolation operator  $\mathcal{I} : C(\bar{\Omega}) \rightarrow \mathcal{S}'$  that interpolates at the nodes of usual kind and reproduces the functions in  $\mathcal{S}'$ . As the operator  $\mathcal{I}$  is linear and the  $\varphi_i$  form a partition of unity, we can decompose the functions  $v \in \mathcal{S}'$  in the kernel of  $\Pi$  into the sum of the functions

$$(4.2) \quad v_i = \mathcal{I}(\varphi_i v) - \Pi(\mathcal{I}(\varphi_i v))$$

in the modified subspaces  $\mathcal{V}_i$ . The stability of this decomposition in the sense of (3.9) can be deduced in the same way as the stability of the decomposition in the proof of Lemma 3.1 since for the functions  $v \in \mathcal{S}'$  in the kernel of  $\Pi$  an estimate

$$(4.3) \quad |\mathcal{I}(\varphi_i v)|_1 \leq c |\varphi_i v|_1$$

holds, which is shown separately for the single elements  $t \in \mathcal{T}'$  using that the restrictions of such functions  $\varphi_i v$  to these elements are second order polynomials.

APPENDIX. ANALYSIS OF A LOCAL PROJECTION OPERATOR

For the convenience of the reader, we give in this appendix a comparatively detailed proof of the estimates (2.5) for the exemplary local linear projection operator  $\Pi$  described in Section 2. Let  $\mathcal{N}$  be the set of the indices of the vertices  $x_i$  of the finite elements in the interior of  $\Omega$ . The operator  $\Pi$  can then be written as

$$\Pi v = \sum_{i \in \mathcal{N}} \alpha_i \varphi_i,$$

with coefficients  $\alpha_i$  that depend linearly on  $v$  and are calculated as follows. At first, the given function  $v$  is locally, separately on each single finite element and regardless of the continuity across the boundaries of the elements, approximated by its  $L_2$ -orthogonal projection onto the space of linear functions. The coefficient  $\alpha_i$  is then a weighted mean of the values of these linear functions at the node  $x_i$  under consideration, weighted according to the contribution of the involved elements to the area or the volume of the patch  $\omega_i$ , the support of the basis function  $\varphi_i$ . The constant functions  $x \rightarrow \alpha_i$  satisfy the local  $L_2$ -norm estimate

$$\|\alpha_i\|_{0,\omega_i} \lesssim \|v\|_{0,\omega_i}$$

over these patches, where the constant on the right-hand side depends solely on the space dimension. Let the patch  $\omega_i$  be the union of the elements  $t_1, \dots, t_n$  and let  $v_1, \dots, v_n$  be the corresponding local  $L_2$ -orthogonal projections of  $v$  onto the space of linear functions. Let  $|\omega_i|$  and  $|t_k|$  be the areas or volumes of  $\omega_i$  and the  $t_k$ . Then

$$\|\alpha_i\|_{0,\omega_i}^2 = |\omega_i| \left( \frac{1}{|\omega_i|} \sum_{k=1}^n |t_k| v_k(x_i) \right)^2 \leq \sum_{k=1}^n |t_k| v_k(x_i)^2.$$

Transformation to a reference element yields the estimate

$$\sum_{k=1}^n |t_k| v_k(x_i)^2 \lesssim \sum_{k=1}^n \|v_k\|_{0,t_k}^2$$

of the right-hand side, with a constant that depends only on the space dimension. As the  $L_2$ -norms of the linear functions  $v_k$  over the  $t_k$  are less than or equal to the  $L_2$ -norms of  $v$  over the  $t_k$ , this proves the estimate above for the  $\alpha_i$ .

To prove the estimates (2.5), we use that the functions in  $H_0^1(\Omega)$  can be considered as functions in  $H^1(\mathbb{R}^2)$  and  $H^1(\mathbb{R}^3)$ , respectively, with value zero outside  $\Omega$ . Because the hat functions  $\varphi_i$  form a partition of unity on  $\Omega$ ,

$$v - \Pi v = \sum_{i \in \mathcal{N}} \varphi_i(v - \alpha_i) + \sum_{i \notin \mathcal{N}} \varphi_i v.$$

On a given element only the functions  $\varphi_i$  assigned to its vertices are different from zero. The square of the  $H^1$ -seminorm of the error can therefore be estimated as

$$|v - \Pi v|_1^2 \lesssim \sum_{i \in \mathcal{N}} |\varphi_i(v - \alpha_i)|_1^2 + \sum_{i \notin \mathcal{N}} |\varphi_i v|_1^2.$$

Let  $B_i$  be the ball with center  $x_i$  of minimum diameter that covers the patch  $\omega_i$  and let  $h_i$  be its radius. As  $|\nabla \varphi_i| \lesssim h_i^{-1}$  by the shape regularity of the elements,

$$|\varphi_i(v - \alpha_i)|_1 \lesssim h_i^{-1} \|v - \alpha_i\|_{0, \omega_i} + |v|_{1, \omega_i}.$$

As the linear functional  $v \rightarrow \alpha_i$  reproduces the value of constant functions,

$$\|v - \alpha_i\|_{0, \omega_i} \lesssim \|v - \alpha\|_{0, \omega_i} \leq \|v - \alpha\|_{0, B_i}$$

holds for all constants  $\alpha$  and, in particular, for the mean value  $\alpha$  of the function  $v$  over the ball  $B_i$ . The Poincaré inequality for balls leads therefore to the estimate

$$\|v - \alpha_i\|_{0, \omega_i} \lesssim h_i |v|_{1, B_i},$$

with a constant that is, of course, independent of the radius  $h_i$  of  $B_i$ . For the terms associated with the inner vertices, thus finally,

$$|\varphi_i(v - \alpha_i)|_1 \lesssim |v|_{1, B_i}.$$

The boundary terms can be treated with a local variant of the Friedrichs inequality. Here we prefer to proceed in a similar way as with the inner vertices. At first,

$$|\varphi_i v|_1 \lesssim h_i^{-1} \|v\|_{0, \omega_i} + |v|_{1, \omega_i}.$$

As polygonal domain,  $\Omega$  satisfies an exterior cone condition. That is, for the  $B_i$  assigned to the vertices  $x_i$  on the boundary of  $\Omega$  there is constant  $c$  such that

$$|B_i \cap \Omega| \leq c |B_i \setminus \Omega|.$$

This constant is independent of  $i$  and depends at most on an upper bound for the diameters of the balls. The  $L_2$ -distance of a function  $v$  in  $L_2(B_i)$  to its mean value over the part of  $B_i$  outside  $\Omega$  can therefore, analogously to the reasoning above, be estimated by its  $L_2$ -distance to the mean value over  $B_i$  itself. As the mean value of the given functions  $v$  over the part of  $B_i$  outside of  $\Omega$  is zero, this leads, again by means of the Poincaré inequality for balls, to the estimate

$$\|v\|_{0, \omega_i} \lesssim h_i |v|_{1, B_i}.$$

For the terms associated with the vertices on the boundary, then

$$|\varphi_i v|_1 \lesssim |v|_{1, B_i}.$$

Since the balls  $B_i$  form, because of the shape regularity of the finite elements, a locally finite covering of  $\Omega$ , one obtains finally the estimate

$$|v - \Pi v|_1 \lesssim |v|_1,$$

with a constant that depends only on the shape regularity of the finite elements and the constant from the exterior cone condition in the form given above. This implies the stability of II. Using that for all square integrable functions  $w$

$$\|h^{-1}\varphi_i w\|_0 \lesssim h_i^{-1}\|w\|_{0,\omega_i}$$

holds, the approximation property follows by the same arguments.

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